CLIMATE CHANGE IMPACTS ON WATER FOR AGRICULTURE IN CALIFORNIA: A CASE STUDY IN THE SACRAMENTO VALLEY

WHITE PAPER

A Report From:
California Climate Change Center

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Arnold Schwarzenegger, *Governor*

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

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The California Climate Change Center (CCCC) is sponsored by the PIER program and coordinated by its Energy-Related Environmental Research area. The Center is managed by the California Energy Commission, the Scripps Institution of Oceanography at the University of California at San Diego, and the University of California at Berkeley. The Scripps Institution of Oceanography conducts and administers research on climate change detection, analysis, and modeling; and the University of California at Berkeley conducts and administers research on economic analyses and policy issues. The Center also supports the Global Climate Change Grant Program, which offers competitive solicitations for climate research.

The California Climate Change Center Report Series details ongoing Center-sponsored research. As interim project results, these reports receive minimal editing, and the information contained in these reports may change; authors should be contacted for the most recent project results. By providing ready access to this timely research, the Center seeks to inform the public and expand dissemination of climate change information; thereby leveraging collaborative efforts and increasing the benefits of this research to California's citizens, environment, and economy.

For more information on the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier/ or contact the Energy Commission at (916) 654-5164.

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Abstract

Global climate change has the potential to dramatically alter hydrologic conditions in California by changing the spatial and temporal patterns of snow accumulation and snow melt. The water management infrastructure in California has been designed and is operated in accordance with historic hydrologic patterns. Understanding if and how this infrastructure can be managed in the face of global climate change in order to meet the array of vital water management objectives for the system is a critical research question addressed by the impacts investigation conducted by the Climate Action Team in response to Executive Order S-3-05 issued by California Governor Arnold Schwarzenegger. This effort included the application of three different water models run under four different global climate model (GCM)/emission scenario combinations. The goal was to begin to understand the potential impacts of and adaptation to global climate change and to evaluate the utility of various tools in refining this understanding in the future.

The current study presents an application of the Water Evaluation and Planning (WEAP) system, developed by the Stockholm Environment Institute, for California's Sacramento River Basin. WEAP was used to evaluate the impact of four future climate scenarios on agricultural water management in the region, and to investigate whether water management adaptation could reduce potential impacts. The four climate scenarios were derived by downscaling the output from two GCMs (Parallel Climate Model and Geophysical Fluid Dynamics Laboratory) and two emission scenarios (A2 and B1) combinations to a 1/8 degree grid over California. The Sacramento Valley WEAP application sampled these climate fields to provide input to a model of the Sacramento River Basin that disaggregates the basin into 64 sub-watersheds. Each of these sub-watersheds is described by an internal rainfall runoff module that dynamically calculates runoff to streamflow, evaporative demand, and surface water/groundwater interactions. These climate-derived hydrologic conditions drive the simulated operation of a representation of the installed water management infrastructure in the region. As such, WEAP is an integrated hydrology/water resources systems model that allows for assessment of climate change impact and adaptation in the water sector based solely on future climate time series. The integrated nature of WEAP is unique among the tools that were used as part of the water resources portion of the impacts investigation.

The model was applied under two formulations, one where cropping and irrigation management patterns remained fixed over the course of a 100-year simulation and one where copping and irrigation management patterns evolved over the course of the 21st century along with the climate. Model runs under all four scenarios showed the largest impacts at the end of the 100-year simulations. In particular, the GFDL/A2 combination produced a downscaled climate series that included a major drought during the final 15 years of the coming century. With no adaptation, a lack of sufficient surface water to meet elevated evaporative demand for irrigated crops led to a dramatic increase in groundwater pumping and a coincident decline in simulated groundwater levels. All simulations also resulted in much lower reservoir levels in

the late summer and early fall as simulated operations kept pace with the increases in evaporative demand associated with higher temperatures.

When adaptation, in terms of shifting cropping and irrigation technology patterns, was allowed to occur, the amount of groundwater pumping between 2070 and 2100 was reduced. While the carryover reservoir storage was not significantly increased, deliveries to meet growing urban demand in the system became increasingly reliable when agriculture could satisfy evaporative demand with a reduced level of water input.

1.0 Introduction

Executive Order S-3-05 issued by California Governor Arnold Schwarzenegger included a requirement that the Secretary of the California Environmental Protection Agency shall report to the Governor and the State Legislature by January 2006 and biannually thereafter on the impacts to California of global warming, including impacts to water supply, public health, agriculture, the coastline, and forestry, and shall prepare and report on mitigation and adaptation plans to combat these impacts. This paper is part of a collection of white papers developed in response the Governor's executive order and, as such, implicitly relies upon the findings of the full suite of documents.

With regards to water resources, the call in the executive order recognizes that climate change has the potential to dramatically alter the hydrologic patterns to which water management arrangements in California must respond. Indeed, recent research suggests that change is already afoot with noticeable declines in the state's vital snow pack observed over the past decades (see the companion paper by Cayan et al., 2006a).

While the level of detail associated with future climate scenarios and associated hydrologic responses increases with the publication of this collection of white papers prepared in response to the Governor's executive order, it has been clear for some time that changes in the way water is managed in the agricultural sector, or adaptation, may accompany future climate change. Chapter 6 of the 3rd United States National Communication under the United Nations Framework Convention on Climate Change (U.S. Department of State 2002) offers a robust inventory of potential impacts and adaptations relating to land cover, agriculture, forests, water resources, coastal areas and marine resources, and human health. Information in Chapter 6 pertaining to agriculture and water resources is particularly pertinent to the current study on climate change impacts on water for agriculture in California. For the 3rd National Communication, insights in these areas were derived from the activities of the National Agriculture Assessment Group (NAAG) and the National Water Assessment Group (NWAG).

At a national level, NAAG concluded that without any adaptation, irrigated agriculture's need for water will decline approximately 5–10 percent for 2030 and 30–40 percent for 2090 in the context of two primary climate scenarios evaluated as part of the National Assessment process, due to increased precipitation and shortened growing periods (Reilly et al. 2001). [1] The assumptions with respect to precipitation and associated water availability used in arriving at these conclusions were based on the work of NWAG, in particular the large-area runoff estimations for the nation (Wolock and MaCabe 1999).

The implicit assumption invoked by NAAG in arriving at this conclusion was that water supplies would be available to meet irrigation water demands. This implies that either available water supplies are well distributed in space and time or that the installed water management infrastructure can be managed to cover any spatial and temporal imbalance between supply and demand. Invoking this assumption was appropriate

1. This shortening is linked to anticipated increases in CO_2 fertilization from the atmosphere.

given the broad goals of the National Assessment process. Nonetheless, according to the NWAG report, research indicates that U.S. watersheds with a substantial snow pack in winter will experience major changes in the timing and intensity of runoff as average temperatures rise. Reductions in spring and summer runoff, increases in winter runoff, and earlier peak runoff are common responses to rising temperatures. The ability of existing systems and operating rules to manage these changes has not been adequately assessed (Gleick et al. 2000). The current California impacts investigation responds directly to this call

Published climatologic and hydrologic scenarios for California suggest that in the future the snow line will be found at higher elevations, that the peak runoff period will occur earlier, and that mountain watersheds will be free of accumulated snow earlier. California is endowed with a substantial and sophisticated water management infrastructure which is operated to meet an array of objectives, including agricultural and municipal and industrial (M&I) water supply, ecosystem enhancement, hydropower, flood control, and recreation. Determining whether these multiple objectives are compatible and attainable in the face of climatic and hydrologic change requires that the important elements of the water supply infrastructure be considered when analyzing future balances between water supply and demand.

In 2001 the Global Change Research Program within the Office of Research and Development at the U.S. Environmental Protection Agency, motivated in part by the NWAG findings, initiated a research effort designed to generate a suitable analytical framework for (1) assessing the potential impacts of climate change on the nation's water resources and aquatic ecosystems and (2) evaluating possible adaptation strategies. One of the funded research teams comprised the National Center for Atmospheric Research (NCAR), the Stockholm Environment Institute (SEI), and the Natural Heritage Institute (NHI). This team used California's Sacramento Valley water system as a case study for the development of its analytical framework, including the Sacramento and Feather Rivers, associated tributaries, and the Trinity River down to the point of diversion towards the Sacramento Valley. The analytical framework generated by the EPA-funded case study has been refined and extended as part of the current investigation of potential climate change impacts in California called for by Governor Schwarzenegger. The goal of the investigation is to determine if future climate change will result in different patterns of agricultural water management relative to the current situation, and whether a first, but by no means comprehensive, set of potential adaptations can assist in reducing potential impacts.

In implementing the original EPA-funded research initiative, the Sacramento research team used the Water Evaluation and Planning (WEAP) system initially developed by SEI as a point of departure. In its original formulation, WEAP was a generic water resource systems simulation model in which exogenous information on water supply, water demand, and water regulation was used to simulate how available water should be allocated under a range of scenarios. This was also the approach used to develop CalSim-II, the water planning model for the Central Valley water system developed by the California Department of Water Resources (DWR) and the United States Bureau of Reclamation (USBR). Like CalSim-II and an increasing number of water resource simulation models, WEAP uses an optimization routine to determine an appropriate water allocation pattern within a given model time step as bounded by a set of simulated constraints.

Within the water resource systems logic included in the original version of WEAP, however, the Sacramento research team embedded a watershed hydrology module. The implications of this integration of hydrology and water resource systems are profound, particularly in terms of the ability to assess the potential impacts of climate change on a heavily managed water system like the one found in California. In essence, this integration allowed WEAP to be run directly using alternative future climate scenarios without having to externally translate the implications of these climate scenarios into hydrologic responses. As will be seen when the results of the WEAP case study are compared to the other water sector investigations included in this study, integration allows for analysis of the future scenarios developed by Cayan et al. (2006b) that are unbounded by a reliance on historical hydrologic patterns. Analysis in the WEAP framework flows directly from the future climate scenarios and not from a perturbation of the historic hydrology as was necessary in applying CalSim-II and CALVIN to the question of potential climate change impacts in the water sector.[2] The WEAP model itself is described in greater detail in **Section 2** of this paper.

The results of the original EPA-funded research were published in a series of peer-reviewed articles (Yates et al. 2005a, 2005b, 2005c). These papers describe the steps taken to calibrate the model to observed conditions in the Sacramento Valley water system during the period between 1960 and 1999. The papers attracted the attention of the California Climate Change Center (CCCC) at the University of California, Berkeley—one of the managing entities for the current investigation for the Governor. The Berkeley CCCC felt that the WEAP model could provide a desirable framework for the research they wished to conduct on the economics of water use in California. Their goal has been to develop a simulation model of how agricultural and urban groups use water in California given economic and institutional constraints. This mixed simulation/optimization approach could complement the pure optimization tool, CALVIN, developed by the University of California, Davis.

A key concern was the ability to disaggregate the analysis to the level of individual water districts, or small groups of water districts with reasonably similar economic and institutional characteristics, because the water district is the level at which most key decisions on agricultural water use are made in California. Another concern was to find a hydrologic modeling platform capable of representing water resource management at the district level based on empirical behavioral relationships that respond to economic as well as hydrological conditions. The Berkeley researchers joined the staff of NHI in

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2. As stated, CalSim-II is a planning model of California's State Water Project (SWP) and the federal Central Valley Project (CVP), developed jointly by the California Department of Water Resources (DWR) and U.S. Bureau of Reclamation (USBR). CALVIN is a California-wide economic-engineering optimization model for water supply and environmental purposes developed at the University of California.

developing this complementary analysis that focuses on potential climate change impacts on the agricultural sector in the Sacramento Valley.

Rather than accepting the Sacramento model in the formulation presented in the peer-reviewed articles, however, the CCCC-NHI research team implemented a series of refinements prior to deploying the model to simulate the agricultural water sector impacts of the four GCM/emission scenario combinations adopted for the current investigation (PCM A2, PCM B1, GFDL A2, GFDL B1).[3] These refinements included the following:

- The disaggregation of the regional mass-balance computational units used in the original model into smaller units defined loosely on water district boundaries. In the original model formulation, there were eight computational units on the Sacramento Valley floor, one of which has been divided into 11 units as part of the current investigation.
- The introduction of econometric expressions that allow for the dynamic determination of cropping patterns as a function of climatic and water supply variables. In the original model formulation, the cropping pattern was an imposed and static input to the model.
- The introduction of the assumption that changes in irrigation management technology will allow for similar levels of crop evapotranspiration (ET) demand to be met with less applied water. In the original model formulation, the parameters related to irrigation management were defined in order to mimic historic applied water levels associated with common crops. As the WEAP model includes a dynamic representation of hydrology it can track all of the implications of changes in the level of applied water, including changes in surface runoff, deep percolation, groundwater–surface water interaction, and the operation of applied infrastructure. While the basinwide water balance may not be significantly changed as a result of increases in irrigation efficiency, WEAP can track the different spatial and temporal distributions of water under climate change scenarios. These have potentially important implications for local water management decision making.

Each of these refinements was designed to give a finer resolution on the potential impacts of climate change and to be able to investigate in some detail whether adaptations made in the agricultural water use sector could mitigate the potential impacts of climate change. Model changes made to implement these refinements are described in greater detail in **Section 3**.

Having implemented these refinements, the model was run for each of the GCM/emission scenario combinations adopted for the current investigation (PCM A2, PCM B1, GFDL A2, GFDL B1). **Section 4** opens with a discussion of how these climate scenarios compare with historic observations. As the other water sector analyses

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3. From this point on, the Parallel Climate Model will be referred to as PCM and the Geophysical Fluid Dynamics Laboratory model will be referred to as GFDL.

included in this series of papers for the Governor, based on the application of CalSim-II and CALVIN, rely on translation of these climate scenarios into hydrologic response via the use of the Variable Infiltration Capacity (VIC) hydrologic model,[4] Section 4 also presents the results of the WEAP internal hydrology module in some detail and provides a comparison with VIC output. Later parts of Section 4 present the results of the refined Sacramento Valley model in terms of the operation of installed hydraulic infrastructure and the water supply available to the agricultural water use sector under each of these combinations. The analysis presents the potential implications of climate change for the agricultural sector in the Sacramento Valley based first on the assumption that cropping and irrigation management are static, and then for the case where they change dynamically over the course of a simulation.

Section 5 includes some concluding remarks and **Section 6** highlights some future steps that would serve to make WEAP an even more robust tool for climate change analysis in the California water system. Following the list of references in **Section 7** and glossary in **Section 8**, technical appendices (**Appendices A and B**) describe in detail the refinements made to the Sacramento Valley model.

Based on the results reported here, the CCCC-NHI research team hopes to make a convincing case that an integrated hydrology–water resource systems framework that allows for the dynamic simulation of adaptation (such as WEAP) is an essential tool for climate change impact and adaptation analysis for California's vital water sector.

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4. The Variable Infiltration Capacity model (VIC) is a macroscale hydrologic model developed at the University of Washington that solves full water and energy balances.

2.0 WEAP Model Description

The Water Evaluation and Planning (WEAP) system is an integrated decision support system designed by SEI to support water planning that balances water supplies (generated through watershed-scale physical hydrologic processes) and multiple water demands (characterized by spatially and temporally variable allocation priorities and supply preferences). WEAP employs a transparent set of model objects and procedures, accessible through a user-friendly interface, that can be used to analyze a full range of issues and uncertainties faced by water planners, including those related to climate, watershed condition, projected demand, regulatory conditions, operational objectives and available infrastructure. WEAP is being applied in numerous settings around the world and is emerging as one of the most promising water-sector decision support systems (DSS) available. For example, the American Water Works Association Research Foundation (AwwaRF) has adopted WEAP for distribution to its member agencies in the U.S. drinking water industry. More information can be found at the WEAP website (www.weap21.org).

2.1. Sacramento Valley WEAP Application

For a complete description of the Sacramento Valley WEAP application, the reader is strongly encouraged to refer to Yates et al. (2005c). In summary, however, the WEAP application for the Sacramento Valley water system includes the major rivers; the major alluvial aquifers; the major trans-basin diversion from the Trinity River; the main reservoirs (Clair Engle, Shasta, Whiskeytown, Black Butte, Oroville, Almanor, Bullard’s Bar, and Folsom); the major irrigation canals and their associated demand centers (e.g., Tehama-Colusa canal, the Glen-Colusa canal, and others); aggregated irrigation districts that draw water directly from rivers; and the principal M&I water demand centers. Three flood conveyance systems included in the model are the Sacramento Weir and the Yolo and Sutter bypasses. WEAP allows the user to set priorities among different users, such as M&I users and agriculture, to define the preference of a particular user for a particular source, such as surface water or groundwater, and to constrain the transmission of water between sources and users based on physical and or regulatory constraints. In formulating a WEAP application, the user describes the multi-objective nature of most engineered water systems.

This last point merits additional comment. The original EPA call for research proposals sought to develop a framework for climate change impact and adaptation analysis for water resources and aquatic ecosystems that could be used to investigate potential large-scale tradeoffs between various water management objectives. The goal was not to investigate future water supply reliability to individual water users but rather to assess whether the broad range of water uses might remain compatible under what are uncertain future climate scenarios, and if not, whether adaptations were available to reduce potential conflicts.

The critical point to state here is that the WEAP application of the Sacramento River system includes the possibility of allowing users to tap groundwater in times of surface water scarcity and for allocation of water to M&I uses in times of shortage. As such, the system can be used to explore the management tradeoffs intrinsic to the California water system that may accompany future climate change in the state.

2.2. WEAP Hydrology

The hydrology module in WEAP is spatially continuous, with a study area configured as a contiguous set of sub-catchments that cover the entire extent of the river basin in question. This continuous representation of the river basin is overlaid with a water management network topology of rivers, canals, reservoirs, demand centers, aquifers and other features (see Yates et al. 2005a and 2005b for details). Within each sub-catchment (SC), the entire area is fractionally subdivided into a unique set of independent land use/land cover classes that lack detail regarding their exact location within the SC, but which sum to 100% of the SC's area. A unique climate-forcing data set of precipitation, temperature, relative humidity, and wind speed is uniformly prescribed across each SC.

A one-dimensional, two-store, quasi-physical water balance model depicts the hydrologic response of each fractional area within an SC and partitions water into surface runoff, infiltration, evapotranspiration, interflow, percolation, and baseflow components. Values from each fractional area within the SC are then summed to represent the lumped hydrologic response, with the surface runoff, interflow, and baseflow being linked to a river element; deep percolation being linked to a groundwater element where prescribed; and evapotranspiration being lost from the system. Where stream-aquifer interactions are significant, the two-store water balance representation within select SCs can be reformulated by recasting the lower store as a simplified groundwater element that has hydraulic connection to associated river reaches. The hydrology module also includes a snow accumulation/melt routine based on the use of an index temperature approach.

At each time step, WEAP first computes the hydrologic flux, which it passes to each river and groundwater object. The water allocation is then made for the given time step, where constraints related to the characteristics of reservoirs and the distribution network, environmental regulations, as well as the priorities and preferences assigned to points of demands are used to condition a linear programming optimization routine that maximizes the demand "satisfaction" to the greatest extent possible (see Yates et al. 2005a for details). All flows are assumed to occur instantaneously; thus a demand site can withdraw water from the river, consume some, and optionally return the remainder to a receiving water body in the same time step. As constrained by the network topology, the model can also allocate water to meet any specific demand in the system, without regard to travel time. Thus, the model time step should be at least as long as the residence time of the study area. For this reason, a monthly time step was adopted for this Sacramento Basin analysis.

3.0 Model Refinements

The USGS Hydrologic Unit Code (HUC) regions were used to subdivide the original Sacramento Valley WEAP model into sub-catchments. This resulted in multiple water districts being aggregated into larger areas. While each of these areas was divided into several land classes, all of the irrigated area within a sub-catchment was assumed to have access to a common set of water sources and to have the same priority for water allocation. The model also assumed that irrigation technology and the distribution of crops within the irrigated areas were held constant over the period of simulation and were similar to those observed during the recent past. For the purposes of the current study, the CCC-NHI research team improved the resolution of the agricultural water management characterization for the Stone Corral HUC (mid-valley, west of the Sacramento River) by describing smaller areas within the HUC according to their access to water supplies and their various water contracting arrangements. The team also implemented strategies that allowed water demands within irrigated areas to change in response to future climate scenarios by improving irrigation efficiency and changing cropping patterns. The following sections explain these model refinements in further detail.

3.1. Disaggregation

In the original Sacramento Valley WEAP application, 54 USGS HUCs represented the Sacramento basin. For the present analysis, information on water sources and water contracting guided the disaggregation of the Stone Corral HUC into smaller units ("sub-catchments") corresponding to individual irrigation or water districts, or groups of small districts. The rationale for this disaggregation is that water users within a larger HUC can differ in terms of their access to water (e.g., some have no access to surface water) or surface water contracting arrangements (e.g., differences between Central Valley Project Settlement and Project contractors). These differences are better characterized by new sub-catchments constructed to ensure greater homogeneity among water users within a single sub-catchment.

Because of time and resources constraints, the research team disaggregated only the Stone Corral HUC. This HUC covers most of the land immediately west of the Sacramento River (see Figure 1) and contains most of Colusa and Glenn Counties and parts of Sutter and Yolo Counties. Within the Stone Corral HUC, there are more than 49 water districts that hold contracts with the Central Valley Project (CVP). There are also a number of private (non-Project) users, not having contracts with CVP, that rely on groundwater pumping and water abstractions from local streams to irrigate their crops. Another source of variability among users in this HUC is their different crop patterns, with some areas growing only rice while others have more varied crop patterns. This high level of variability among water users in the Stone Corral HUC motivated its selection to develop a more disaggregated hydrologic-economic model of water use in the Sacramento Valley. A detailed description of the disaggregation methodology is presented in Appendix A.

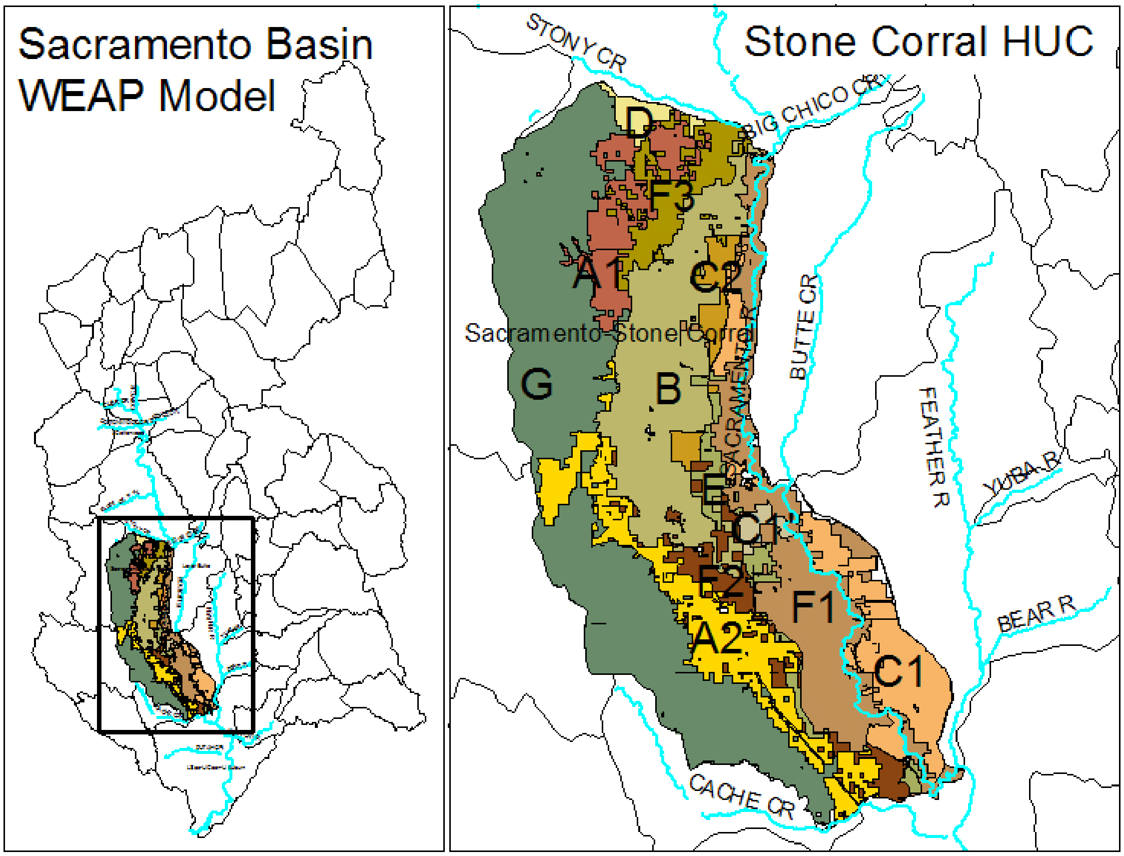

Figure 1. Disaggregation of Stone Corral HUC

3.2. Adaptation Strategies to Climate Change

As previously mentioned, the 3rd National Communication (U.S. Department of State 2002) highlighted a series of potential adaptation strategies for the agricultural sector in the United States. Two of the most prominent were shifting the planning dates of specific crops and introducing new varieties that are more appropriate to a future climate condition. In the Sacramento River system, other potential adaptations can be added to the list: the adoption of improved technologies that raise irrigation efficiency; crop switching, including fallowing; and water marketing whereby irrigation districts in the Sacramento Valley sell water to the Environmental Water Account, or to urban and agricultural users south of the Delta. The point is that any adaptation, perhaps including some not listed above, will respond to economic signals that are driven by public policy, market conditions, and, in a setting like California, the availability of irrigation water supply. Understanding the evolution of this last factor under future climate conditions requires the application of a water resources systems model that tracks the management of the available hydraulic infrastructure.

WEAP is such a tool. More importantly in the context of adaptations, WEAP allows the model user to represent dynamic changes in water management by programming in model parameters that vary over the course of a simulation. These parameter changes can be imposed as exogenous forces upon the model (e.g., as functions of the passage of time) or they can be expressed within the model as a function of the state of the system (e.g., water supply, crop yields, depth to groundwater). Both methods are used here to represent the adaptation strategies listed above.

With regard to improvements in irrigation efficiency, the research team believes that existing and anticipated future regulatory pressures for improved agricultural water use efficiency are likely to lead to increased efficiency such that most crops other than rice will employ drip irrigation by the middle of the century (further details are provided in Appendix B). With cropping patterns and fallowing, the model is formulated so that CVP agricultural and settlement contractors in the Sacramento Valley make simulated cropping decisions in any given year based upon projected water supplies and the current depth to groundwater in regional aquifers. The behavioral rules determining the cropping pattern are based on an econometric analysis based on the historical experience in the region (a complete description is presented in Appendix B.[5]

This paper makes no claim that the adaptations considered in the model cover all possible adaptations in the agricultural sector, or that we have captured all of their relevant details. Instead, this paper attempts to demonstrate how internalizing adaptation within a model that includes both the hydrologic and water management conditions associated with future climate change can help assess how potential tradeoffs in multi-objective water management systems can be handled. The fact that the range of potential adaptations is vast should not detract from the current effort to dynamically include adaptation in a linked hydrology/water management framework. Instead it highlights the enormous power of the tool and motivates additional research.

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5. The third adaptation, increased water marketing by Sacramento Valley farmers, is also viewed as an exogenous time trend driven as much by economic forces outside the valley ("demand pull") as by those within the valley ("supply push"), and is based on assessment that these sales might grow to about 2 million acre-feet per annum by mid-century and about 3.5 million acre-feet towards the end of the century. Due to lack of time, this adaptation has not been programmed into the results presented below.

4.0 Climate Change Impacts on Agriculture in the Sacramento Valley

The Intergovernmental Panel on Climate Change (IPCC) released a Special Report on Emissions Scenarios (SRES) that grouped future greenhouse gas emission scenarios into four separate "families" that depend upon the future developments in demography, economic development, and technological change. Together they describe divergent futures that encompass a significant portion of the underlying uncertainties in the main driving force behind global climate change. These scenario families are summarized in Box 1. For the purposes of this study, outputs from two general circulation models (GCMs) were used to estimate future climate conditions under two SRES scenarios: A2 and B1. By choosing two GCM and two emission scenarios that would be applied to all investigations in response to the Governor's executive order, the Climate Action Team hoped to create a consistent set of output that would represent the range of future climate conditions.

The two GCMs used to generate the future climate conditions for the current investigation were the Parallel Climate Model (PCM) developed at the National Center for Atmospheric Research and the CM2 model developed at the Geophysical Fluid Dynamics Laboratory (GFDL). Outputs from these models were downscaled by applying the methodology developed by Maurer et al. (2002) to create a 1/8 degree gridded data set for daily climate variables. This downscaled daily data set was used to derive average monthly time-series of precipitation, temperature, and wind speed for each of the 54 sub-catchments in the WEAP model. Cayan et al. (2006b) also calculated the relative humidity time series required to run the WEAP hydrology module based on the downscaled climate variables and other grid-scale parameters.

This section of the paper summarizes the predicted changes in precipitation and temperature over the next century. This analysis is followed by a discussion of the impacts of changing precipitation and temperature on the hydrologic response in the upper watersheds above the major reservoirs in the system and a discussion of the impacts of changing temperatures on crop water demands in the irrigated portion of the Sacramento Valley below these facilities. Later subsections discuss how the combined effects of altered water supply and demand regimes influence the ability of the water resources system to be operated to meet defined targets. Section 4.0 concludes by evaluating the relative impact of implementing water management adaptation strategies at the irrigation district level in response to future conditions.

Box 1. Main Characteristics of the Four SRES Storylines

from Nakic´enovic and Swart (2000), *Special Report on Emissions Scenarios*, published by the Intergovernmental Panel on Climate Change

- The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive sources (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B).
- The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
- The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
- The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

4.1. Climatic Analysis

In the following analysis, precipitation and temperature data are presented for the four alternative climate change model/scenario combinations: GFDL A2, GFDL B1, PCM A2, and PCM B1. These climate variables are presented as the averages of the 54 climate locations used as inputs to WEAP, although the trends are very similar throughout the Sacramento Valley. Graphs are presented for four distinct periods: 1960–1999, 2005–2034, 2035–2064, and 2070–2099. Each of the four periods was compared to the historic data set that was used to calibrate the WEAP model over the period 1960–1999 (Maurer et al. 2002). An important caveat to consider when looking at the historical baseline, however, is that neither GCM used estimated historical forcing and, thus, the GCMs do not replicate the exact historical climate. Instead they were calibrated to generate statistically similar climate patterns of the historical period. The historical baseline should be viewed as a reference against which to view the time evolution of climate change impacts associated with each model/scenario combination.

What Is the Historical Baseline?

The actual historical climate was a spatially distributed field of climate variables that was observed at a limited number of climate stations. The WEAP model requires that climate inputs be introduced for each sub-catchment, whether or not a climate station is located within its boundaries. Maurer (2002) produced a grid of interpolated climate variables based on the limited set of observations. The assumptions used to carry out the interpolation are implicit in the output, which may not capture the exact spatial distribution of historic climate fields.

4.1.1. Precipitation

Figure 2 shows changes in annual precipitation. The results are presented as exceedance probability plots, which sort the sequence of years into dry (exceeded in roughly 75%–100% of years), normal (exceeded in roughly 25%–75% of years), and wet years (exceeded in roughly 0%–25% of years) for each of the four periods of our analysis. The graphs show that the two GFDL scenarios predicted a decreasing trend in precipitation over the next century, with wet years showing the largest shift in annual rainfall. The two PCM scenarios showed less pronounced changes in annual precipitation. PCM B1 predicted slightly wetter conditions at the end of the century, while the PCM A2 showed a decrease in precipitation in normal-dry years and an increase in precipitation in normal-wet years.

4.1.2. Temperature

Figures 3 and 4 show changes in average temperature for winter (October through March) and summer (April through September) periods. Hash marks above and below shaded boxes indicate maximum and minimum values. Each of the four scenarios predicted increases in average winter and summer temperatures over the next century. GFDL A2 showed the highest increases in temperature: 3.0°C (5.4°F) for winter and 5.0°C (9°F) in summer. PCM B1 showed the smallest change in temperature: 1.5°C (2.7°F) for winter and 1.4°C (2.5°F) in summer. The GFDL B1 and PCM A2 scenarios predicted intermediate changes in temperature. GFDL B1 predicted changes of 1.9°C (3.4°F) in winter temperature and 2.8°C (5°F) in summer temperature. PCM B1 predicted changes of 2.2°C (4°F) in winter temperature and 2.5°C (4.5°F) in summer temperature.

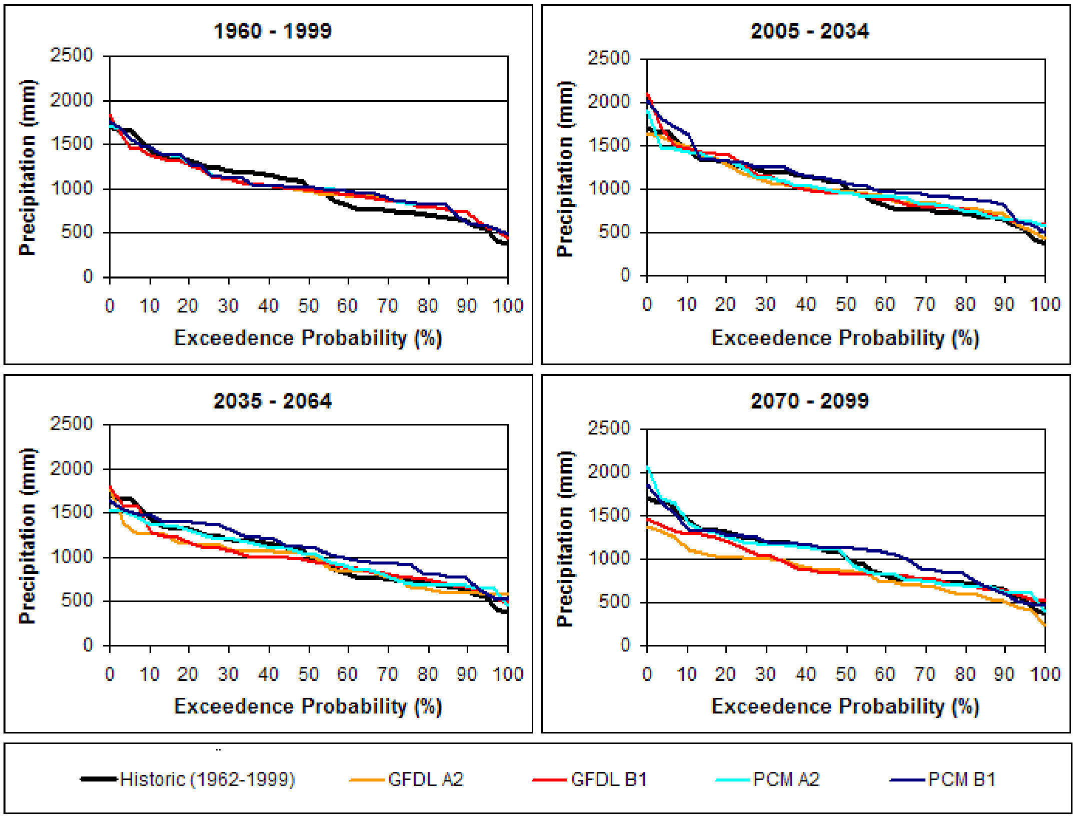


Figure 2. Total annual precipitation

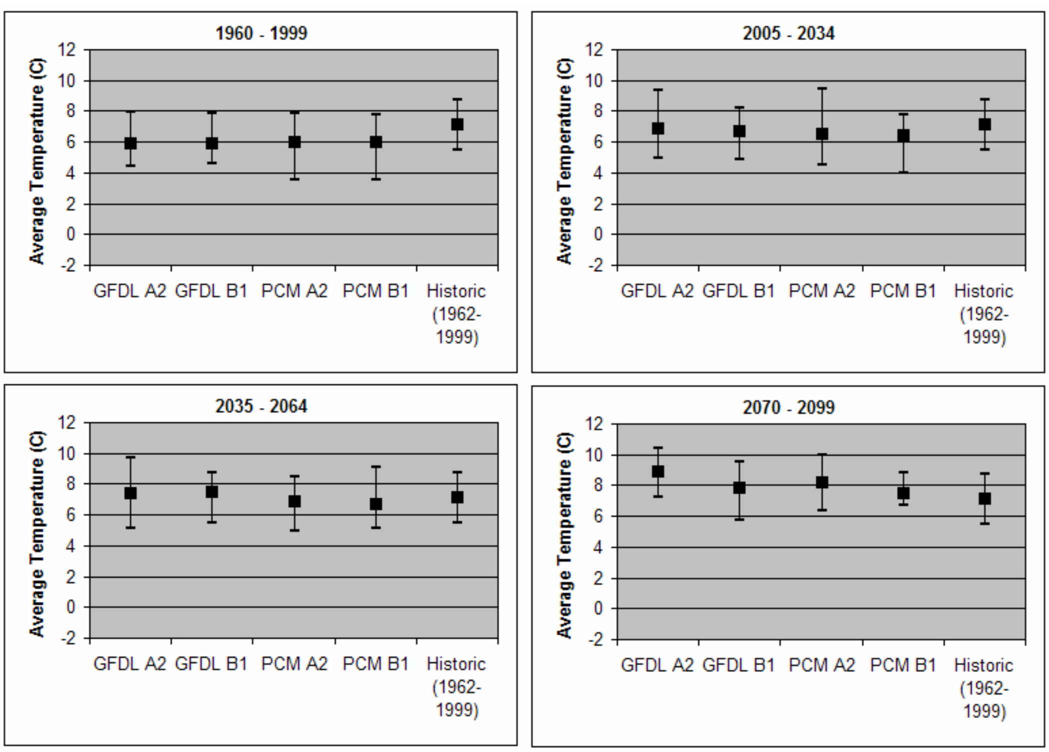


Figure 3. Average, maximum, and minimum temperatures October–March

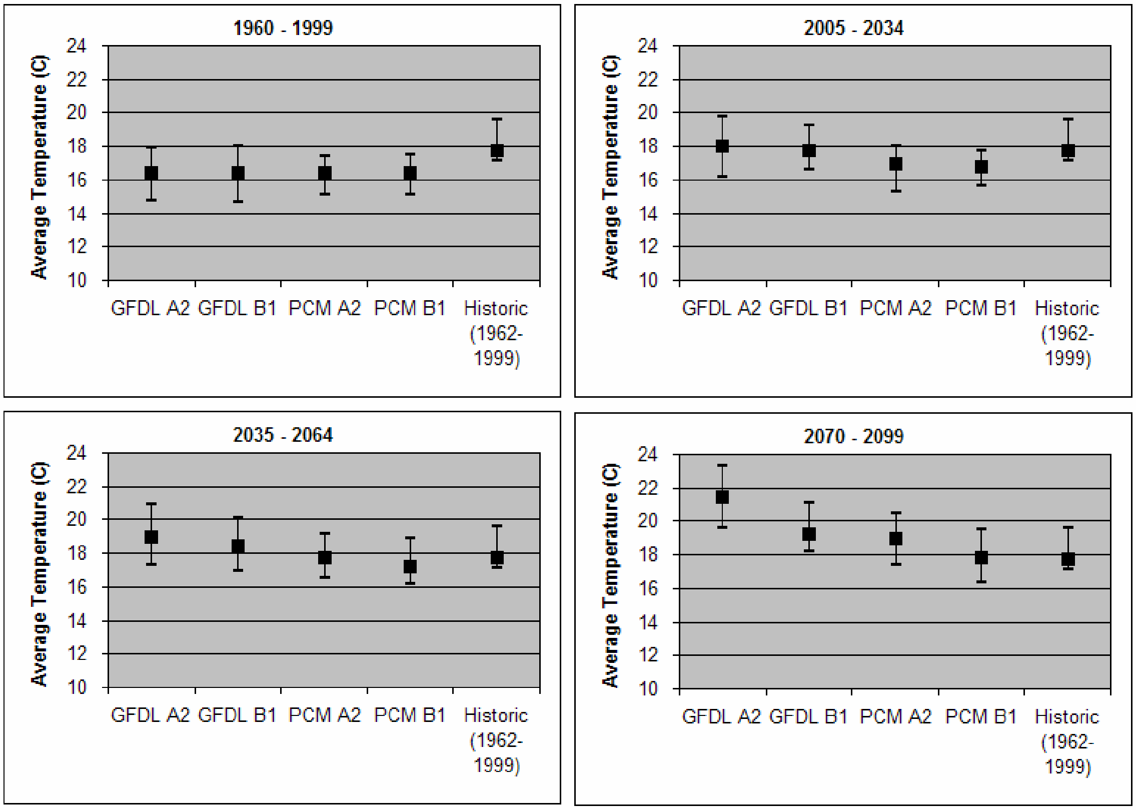


Figure 4. Average, maximum, and minimum temperatures April–September

The graphs depicting the winter and summer temperatures for the 1960–1999 period demonstrate clearly how the simulated climate variables from the historical period do not match this historical baseline. A direct comparison with the historical baseline is complicated, however, by the fact that the historic data are influenced by the implicit assumptions of the interpolation routine used by Maurer et al. (2002), which may not faithfully capture the actual continuous historic climate fields. Assuming that the interpolated historical data do represent the historic climate fields, then the climate scenarios selected by the Climate Action Team, which start from relatively cool conditions, suggest that the analysis that flows from these climate scenarios represents a relatively conservative analysis of future climate change impacts.

4.2. Hydrologic Analysis

This section presents the impacts of the climate change scenarios on the Sacramento Basin hydrology, with a focus on inflows to the three major reservoirs in the basin: Lake Shasta, Lake Oroville, and Folsom Lake. The objectives of this hydrologic analysis are as follows:

- Show how well WEAP represents historic hydrologic conditions, by comparing historic data (as characterized by CalSim-II input files) with outputs of WEAP run for historic climatic conditions (Table 1).

- Compare streamflow data generated by VIC and WEAP models (Table 2 and Figure 5).
- Analyze hydrologic conditions for the climate change scenarios. The focus here will be on changes in annual inflows (Figures 7 through 9), in streamflow timing (Figure 10), and in drought persistence (Figure 11).

4.2.1. WEAP simulation of historic reservoir inflows

The following equation shows a comparison between historic hydrologic conditions and outputs of WEAP run using historic climatic data (Maurer et al. 2002) for the three major watersheds in the Sacramento Basin. The model's goodness of fit for each of the watersheds was judged using the following equation (Table 1 shows the results for the three watersheds):

$$R^2 = 1 - \frac{\sum (WEAP_i - CalSim_i)^2}{\sum CalSim_i^2}$$

Where $WEAP_i$ = annual inflow as generated by WEAP and $CalSim_i$ = historic annual inflow.

The results show that WEAP has a very good representation of both Feather and Sacramento-Pit streamflows but not as good for the American River.

Table 1. Goodness of fit for WEAP results

Watershed (reservoir inflow)	R^2
Sacramento-Pit (Shasta)	0.99
Feather (Oroville)	0.97
American (Folsom)	0.68

4.2.2. Comparison of WEAP and VIC predictions of reservoir inflows

This section compares VIC and WEAP hydrologic conditions under climate change scenarios for the three major watersheds in the Sacramento Basin. The comparison between the two models is consistent for each of the climate change scenarios; Figure 5 shows GFDL B1 results as an example. In order to reduce the number of figures presented in this early draft version, a comparison for just one GCM output is shown: GFDL B1. Again R^2 is used as defined above as a measure of the goodness of fit between the two models. The results as presented in Table 2 show that VIC and WEAP have a very good agreement for the Sacramento-Pit and Feather Rivers with less correspondence for the American watershed.

Table 2. R2 between WEAP and VIC results

Watershed (reservoir inflow)	R^2
Sacramento-Pit (Shasta)	0.99
Feather (Oroville)	0.95
American (Folsom)	0.85

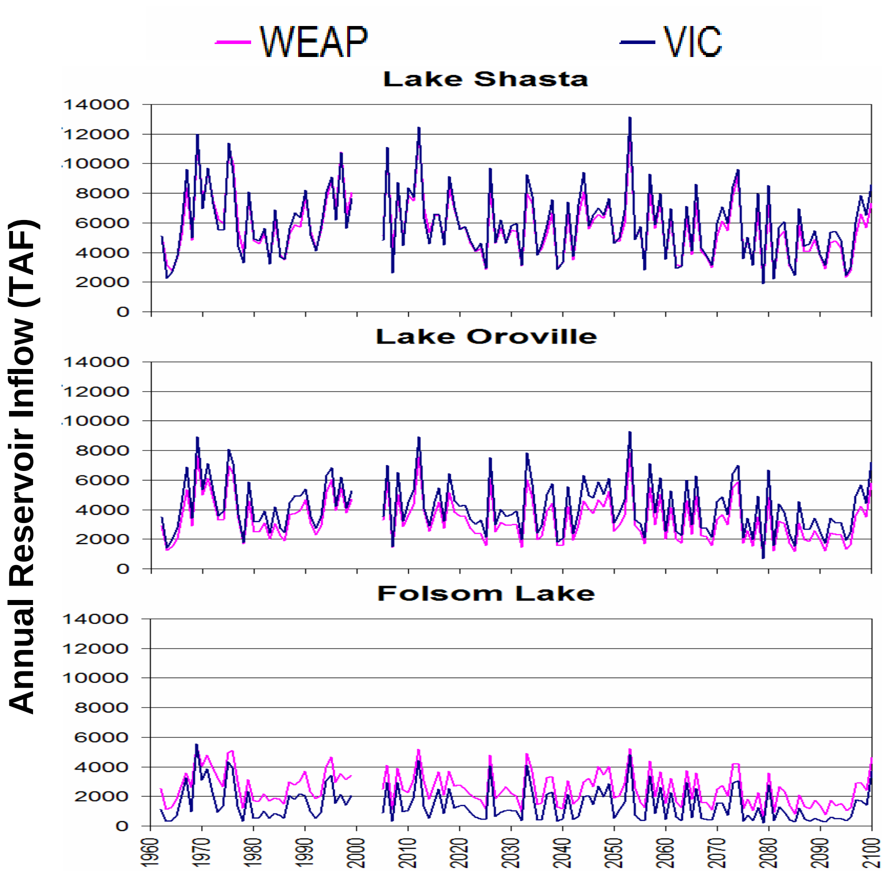


Figure 5. Comparison of WEAP and VIC inflows to Shasta, Oroville, and Folsom Reservoirs for climate change conditions under the GFDL B1 scenario (inflow given in thousand acre-feet)

The deviation between the simulated WEAP input to Folsom Lake and the simulated VIC inflows raises questions about what is going on in the American River system. One cannot point to a bias in either model, since comparing outputs from different models is complicated by uncertainty about which model is correct. The underlying performance of the hydrologic formulation in the WEAP model was supported, however, when output from a more refined model of the American River was compared with unperturbed natural flows observed in the North Fork of the American River, with good results (Figure 6).

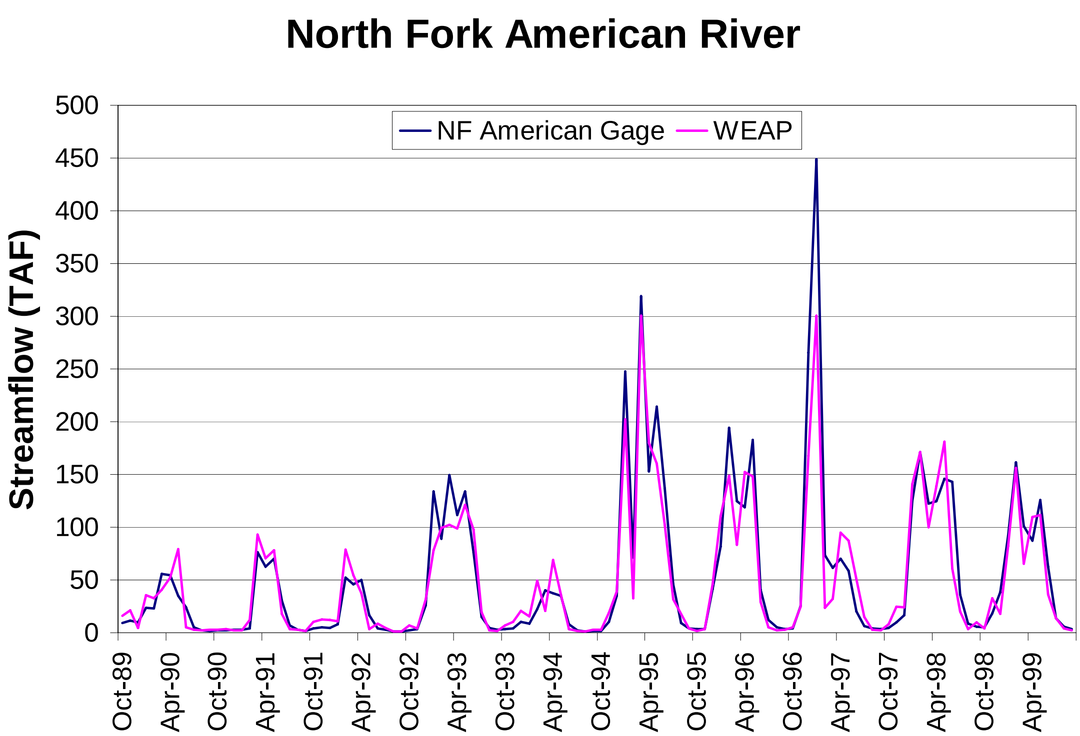


Figure 6. Comparison of WEAP results and observed unaltered natural flows in the North Fork of the American River

4.2.3. Climate change impacts on reservoir inflows

This section focuses on the analysis of three highly relevant aspects of the hydrologic conditions that could be expected under the climate change scenarios included in this assessment: annual inflows to reservoirs, changes to streamflow timing, and drought persistence. These are the factors that are likely to change under climate change and which raise the issue of whether the water management arrangements that exist in the system can respond to these changes.

4.2.3.1. Changes to annual inflows

Figures 7 through 9 show changes in the exceedance probability of annual inflows to major reservoirs in the Sacramento Basin for two time periods: 2035–2064 and 2070–2099. The results presented are consistent with the results shown above in terms of changes in annual precipitation, i.e., PCM B1 is a wet scenario and therefore has higher annual inflows to the major reservoirs, and GFDL A2 is a dry scenario and therefore has lower annual inflows. The other two models fall in between. This finding is consistent with the supposition that a drier climate would reduce the overall water supply.

4.2.3.2. Changes to streamflow timing

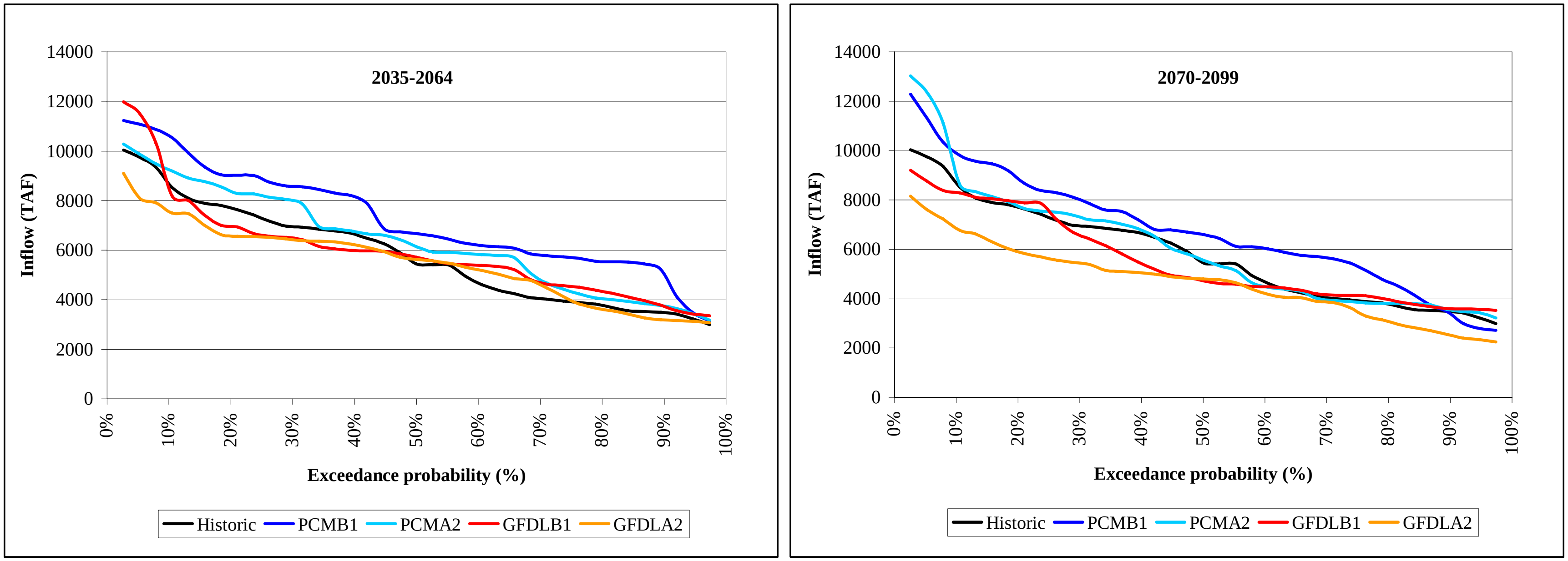
Figure 10 shows changes in monthly average inflows (surrogate for changes in streamflow timing) to major reservoirs in the Sacramento Basin for the 2070–2099 time period. All the scenarios show an earlier timing of streamflows as compared to historic conditions. The impacts are higher for the Feather and American watersheds, which is expected considering that both basins have more dependence on snow melt runoff as much of the Sacramento watershed above Lake Shasta lies below the snow line. The impacts are also higher for those scenarios with higher increases in temperature (e.g., GFDL A2), consistent with the results shown above in terms of changes in temperature. Once again the results are consistent with the supposition that warmer temperatures lead to earlier loss of the snow pack.

4.2.3.3. Changes to drought conditions

A major advantage of the WEAP model is that it can examine scenarios that don't preserve the historic sequence of wet and dry years. Thus, WEAP can simulate conditions under different levels of drought persistence that might occur with climate change. This paper includes an estimate of possible changes in future hydrologic conditions in terms of drought persistence. Drought conditions in the Sacramento Basin were described using a construction of the 40-30-30 Sacramento (Four River) Index. This index is composed of inflows to Shasta, Oroville, and Folsom Reservoirs plus streamflow at Yuba River. Based on the value of this index, a water year is classified as wet, above normal, below normal, dry, or critical. Assuming that a drought will be indicated by a year below the dry threshold, an accumulated deficit representing the positive difference between the "dry" threshold and the 40-30-30 Index was calculated. Deficits are accumulated in consecutive dry years and whenever the index is above the "dry" threshold, the deficit is reset to zero.

Figure 11 shows the accumulated deficits for the historic period (the 1976–77 and early 1990s droughts are apparent), the four climate change conditions included in this analysis, plus one last climate change scenario corresponding to the PCM model run under the A1fi emission scenario. The results show that drought persistence will be smaller for the two PCM scenarios considered in this analysis, but not if the A1fi emission scenario is included. Under A1fi, the prediction is that droughts comparable in magnitude to the early '90s drought will occur with regularity. On the other hand, the GFDL B1 scenario predicts milder conditions as compared to the historic scenario in terms of drought persistence. However, this is clearly not the case under the GFDL A2 scenario, which includes a very severe drought ("mega-drought") during the last 15 years of the century.

The future pattern of drought persistence associated with each GCM/emission scenario combination is directly related to the sequence of climate data associated with each combination. Wet scenarios such as PCM A2, PCM B1, and GFDL B1 produce future climate sequences that contain less dramatic drought conditions than in recent history. More precipitation means fewer droughts. Dry scenarios such as PCM A1fi and GFDL A2 are associated with drought conditions that are more numerous or more severe than in recent history. Less precipitation means more droughts. When considering this information on drought persistence, it is important to keep in mind that the climate time series associated with each GCM/emission scenario combination represents a single realization of the future climate. It would be possible to develop ensembles of future climate time series, which would allow for a more robust depiction of potential future drought conditions. In the interest of time, the Climate Action Team chose not to develop and use ensembles.

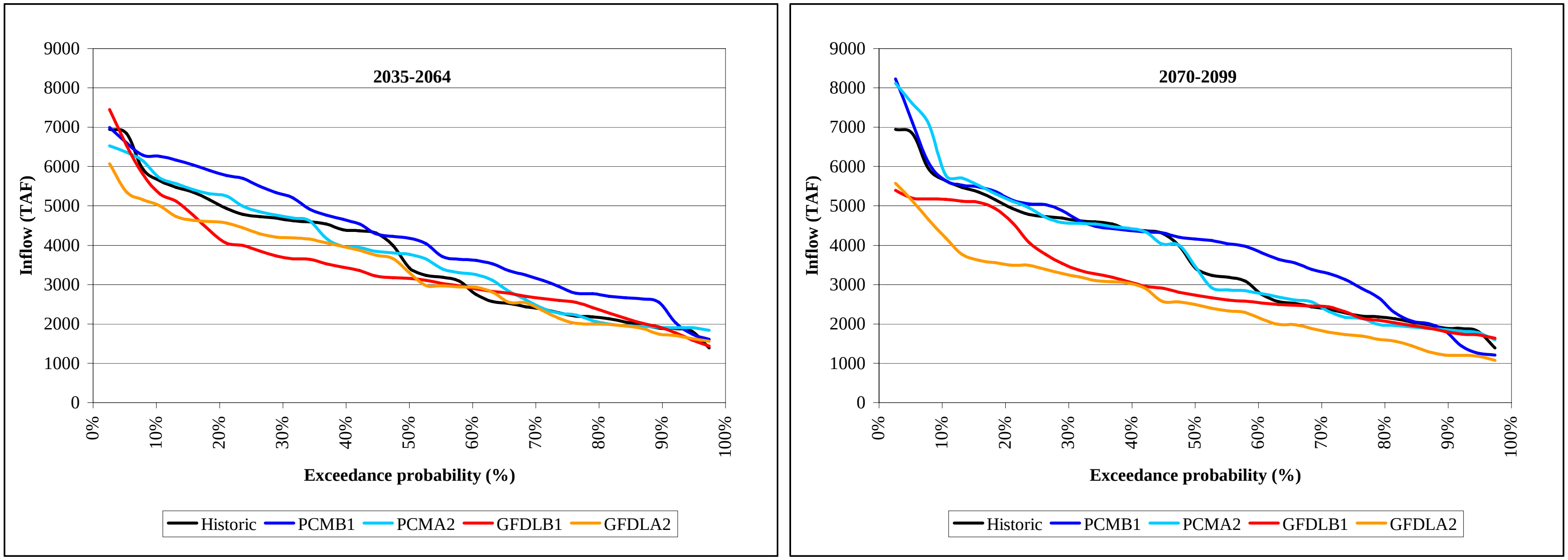


Inflows to Shasta

Historic conditions (1962-1998)	
50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)
5,444	3,479

	GFDL A2		GFDL B1		PCM A2		PCM B1	
	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)
2035-2064	5,621	3,184	5,708	3,734	6,143	3,738	6,666	5,001
2070-2099	4,804	2,518	4,728	3,599	5,561	3,552	6,606	3,381

Figure 7. Exceedance probability of annual inflows to Shasta. Comparison between climate change scenarios and historic conditions.

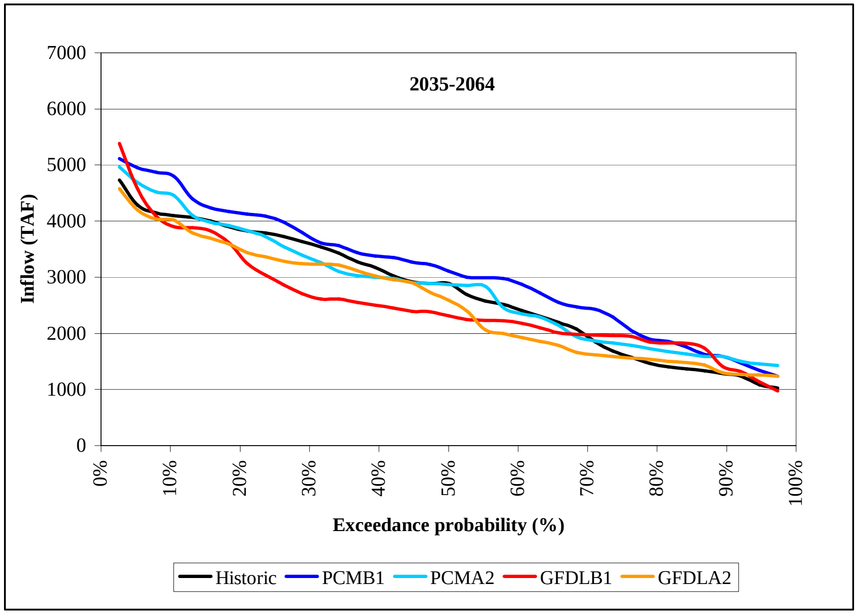


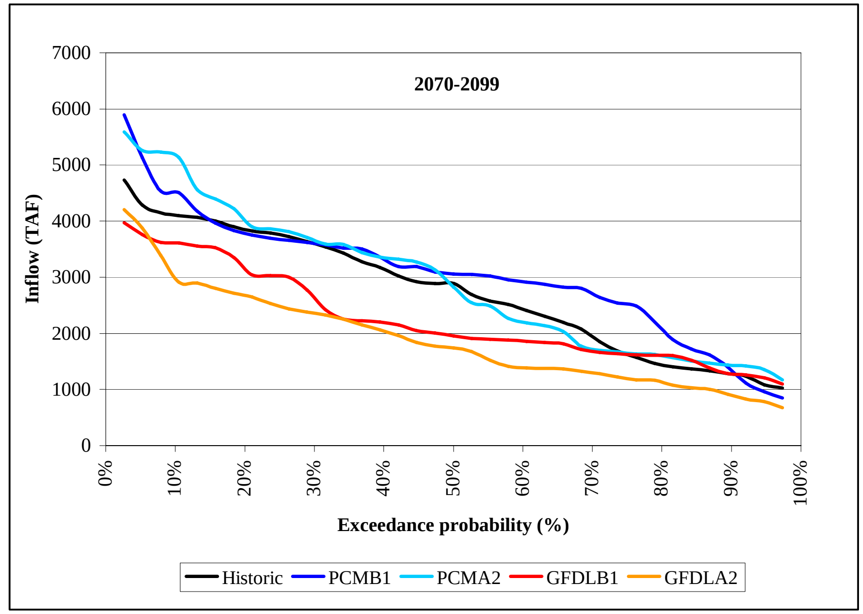
Inflows to Oroville

Historic conditions (1962-1998)	
50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)
3,426	1,895

	GFDL A2		GFDL B1		PCM A2		PCM B1	
	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)
2035-2064	3,305	1,735	3,160	1,893	3,766	1,910	4,181	2,448
2070-2099	2,494	1,203	2,731	1,792	3,465	1,852	4,157	1,750

Figure 8. Exceedance probability of annual inflows to Oroville. Comparison between climate change scenarios and historic conditions.





Inflows to Folsom

Historic conditions (1962-1998)	
50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)
2,886	1,270

	GFDL A2		GFDL B1		PCM A2		PCM B1	
	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)
2035-2064	2,593	1,287	2,314	1,389	2,866	1,572	3,107	1,565
2070-2099	1,739	898	1,950	1,274	2,822	1,433	3,060	1,341

Figure 9. Exceedance probability of annual inflows to Folsom. Comparison between climate change scenarios and historic conditions.

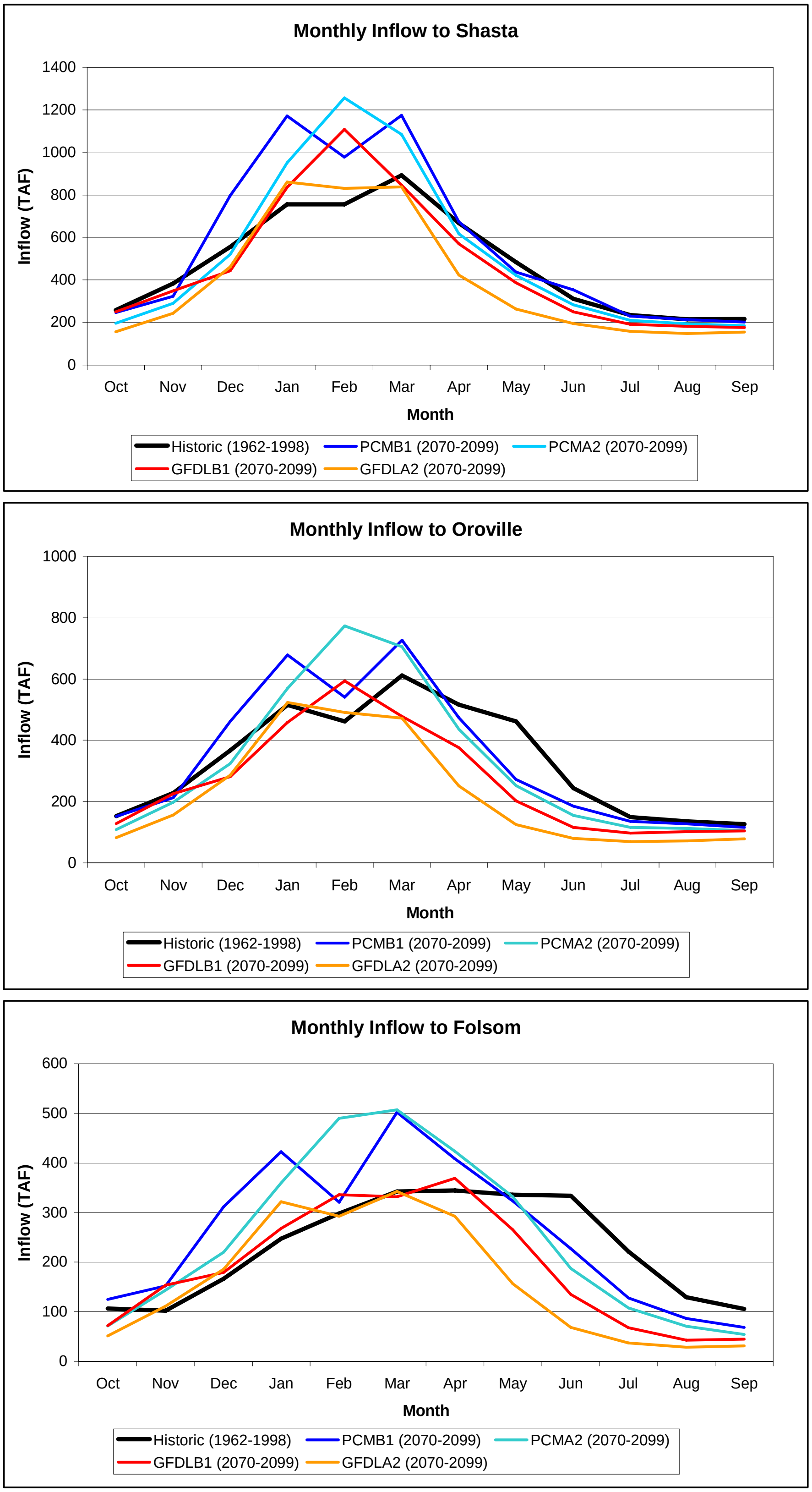


Figure 10. Changes in monthly inflows to Shasta, Oroville, and Folsom Reservoirs

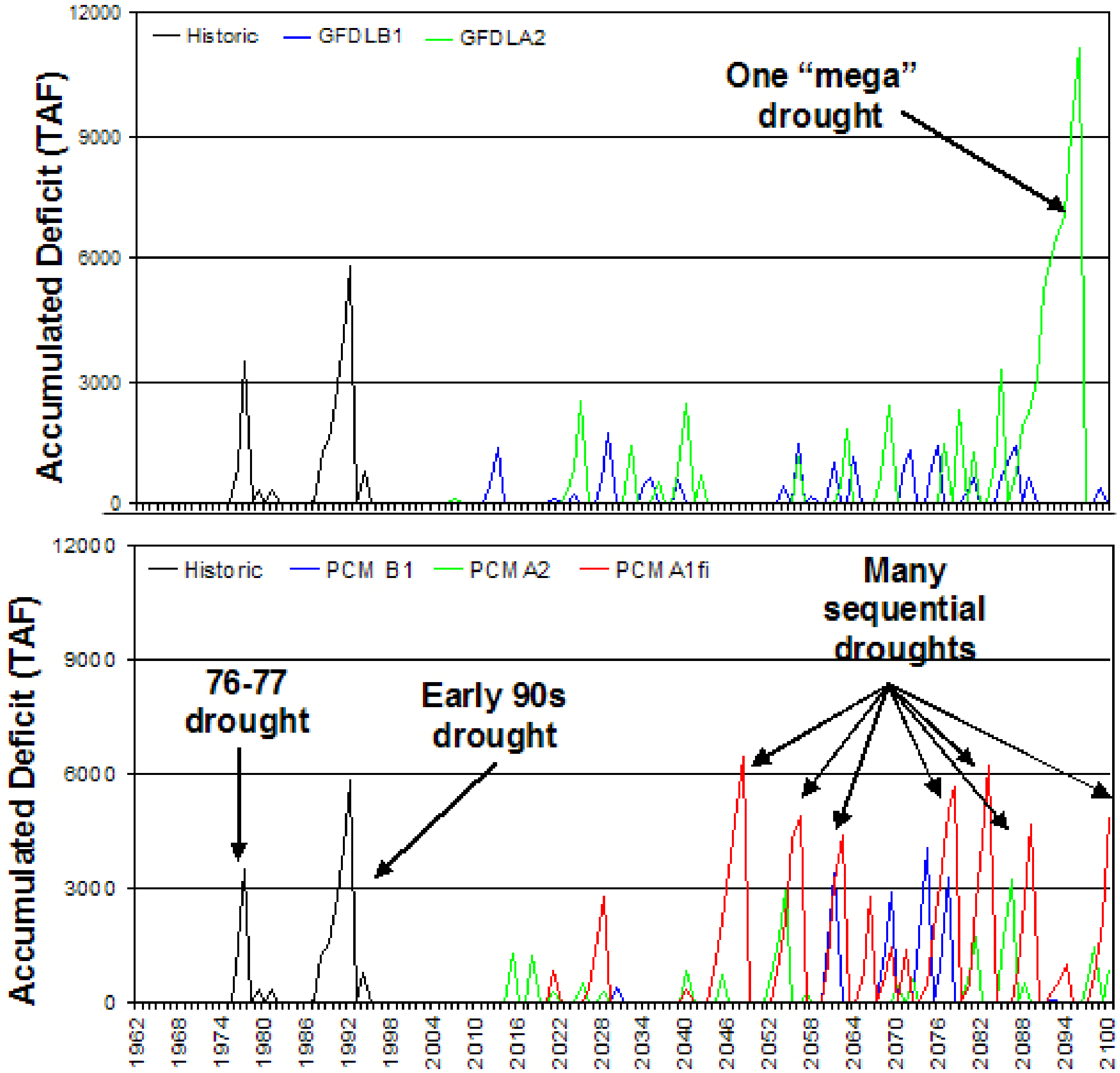


Figure 11. Changes in drought conditions

4.3. Demand Analysis

Annual supply requirements for Sacramento Valley agricultural areas are summarized in Figure 12 and Table 3. These are the sums of the crop water requirements calculated from the future climate time series using WEAP's internal Penman-Montieth routine, adjusted based on assumed losses in delivering water to meet these requirements, for all irrigated crops in a particular sub-catchment. All four scenarios showed an increasing trend in water requirements with time, with the GFDL A2 scenario exhibiting the most pronounced increase. These increasing supply requirements are due primarily to increasing summer temperatures for each of the four scenarios (see Section 4.1).

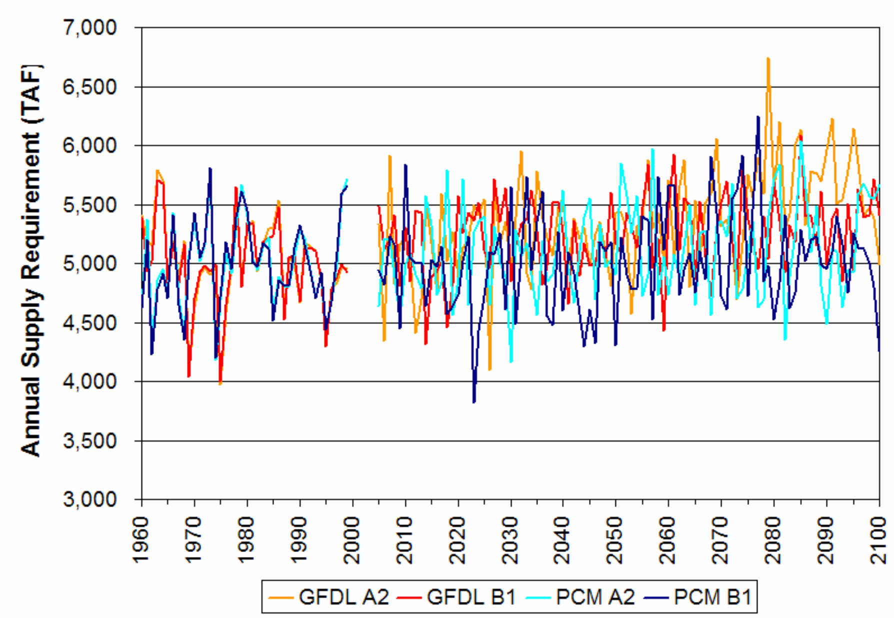


Figure 12. Annual supply requirements: Sacramento Valley agriculture

Table 3. Changes in annual supply requirement: Sacramento Valley agriculture

	GFDL A2			GFDL B1			PCM A2			PCM B1		
	Average Annual Requirement (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Requirement (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Requirement (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Requirement (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)
1960-1999	5,008	0	0%	5,002	0	0%	4,990	0	0%	4,993	0	0%
2005-2034	5,139	131	3%	5,191	189	4%	5,025	34	1%	4,944	-48	-1%
2035-2064	5,297	289	6%	5,231	229	5%	5,131	141	3%	4,979	-13	0%
2070-2099	5,658	650	13%	5,348	345	7%	5,188	198	4%	5,107	115	2%

4.4. Operations Analysis Without Adaptation

This section considers the impacts of each of the climate change scenarios on water supply and delivery. For the purposes of this analysis, the impacts to water supply were evaluated using reservoir carryover storage and groundwater levels as indicators. Delivery reliability under each scenario was evaluated using total annual measures of surface water deliveries and groundwater pumping.

Delivery reliability was evaluated for Sacramento Valley agriculture users. Separate assessments were made for the agricultural areas serviced by the Sacramento and Feather Rivers, because of the different contractual arrangements for these two rivers. It should be noted, however, that project areas (i.e., CVP along the Sacramento River and SWP along the Feather River) are aggregated with non-project agricultural areas for each of these regions. Section 4.4 ends with an analysis of delivery reliability for the Stone Corral HUC, where sub-catchments were distinguished according to their contract types.

4.4.1. Sacramento Valley agriculture

Water districts that have contract agreements for surface water deliveries from the two main water projects—the Central Valley Project (CVP) and State Water Project (SWP)—that dominate agriculture in the Sacramento Valley. Both projects operate large reservoirs on separate rivers that they use to store and release water to their respective contractors. The CVP operates Lake Shasta on the Sacramento River along with storage and diversion infrastructure on the Trinity River. The SWP operates Lake Oroville on the Feather River. Water that is released from these reservoirs is diverted at various control points along the rivers. WEAP simulates the operation of these reservoirs by assuming that water demands in the agricultural areas, as defined by crop water requirements, are the drivers for reservoir releases.

WEAP attempts to satisfy crop water requirements by delivering water through canals and by pumping groundwater. The extent to which it is able to meet the full crop requirements depends upon surface water supplies and capacity constraints on canals and groundwater pumping. Presently, with the exception of CVP contractors in Stone Corral HUC, surface water deliveries to agriculture are not constrained by the amounts specified in water user contracts. For this reason, the interpretation of climate impacts on water supply and delivery is similar for both the CVP and SWP. Therefore, model results for both the Sacramento and Feather River areas are presented together.

Each of the four climate change scenarios was run continuously over a historical period (1960–1999) and a future period (2005–2100) using downscaled GCM climate data. The results of these scenarios are summarized in the following graphs of carryover storage levels for Lake Oroville and Lake Shasta, annual surface water deliveries to agriculture from the Feather and Sacramento Rivers, and, for each basin, annual groundwater pumping by agriculture and groundwater levels. With the exception of groundwater levels, which are presented as time-series graphs, each metric is presented in exceedance probability form for four distinct periods: 1960–1999, 2005–2034, 2035–2064, and 2070–2099. Each of the four periods is compared to a historic baseline that was generated by running the WEAP model over the period 1962–1998 using historical gridded climate data (Maurer et al. 2002).

4.4.1.1. Carryover storage

Carryover storage in Lake Shasta and Lake Oroville was defined as the amount of water remaining in each of these reservoirs at the end of September (i.e., the end of the water year). Simulations showed that carryover storages in both Oroville (Table 4 and Figure 13) and Shasta (Table 5 and Figure 14) decrease with time, with the GFDL A2 scenario experiencing the largest change and the PCM B1 scenario showing only a slight change. This trend is consistent with the inflow hydrographs that were previously discussed in Section 4.2, which showed significant reductions in reservoir inflows with time using the GFDL model and little change in inflows when using the PCM model. Decreases in reservoir carryover storage volumes resulted primarily from decreasing inflows, but were enhanced by increases in surface water deliveries to agriculture (see Section 4.4.1.2).

Table 4. End-of-September storage in Oroville

	GFDL A2		GFDL B1		PCM A2		PCM B1	
	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)
1960-1999	2,725	1,661	2,716	1,639	2,876	1,733	2,858	1,733
2005-2034	2,646	1,723	2,535	1,629	2,775	1,779	2,901	2,483
2035-2064	2,300	1,562	2,378	1,604	2,758	1,541	2,920	1,841
2070-2099	1,684	1,107	2,059	1,563	2,299	1,494	2,677	1,550

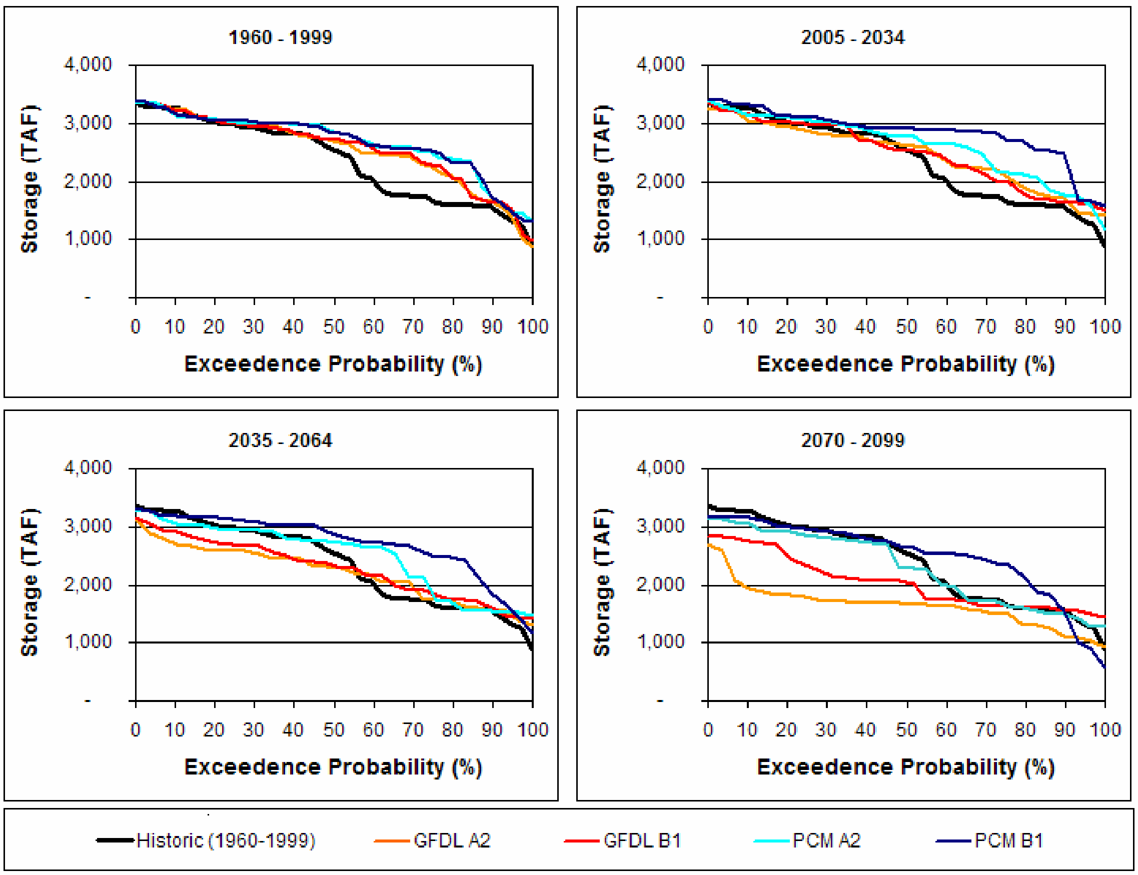


Figure 13. End-of-September Oroville storage

Table 5. End-of-September storage in Shasta

	GFDL A2		GFDL B1		PCM A2		PCM B1	
	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)	50 Percent Exceedence (TAF)	90 Percent Exceedence (TAF)
1960-1999	3,235	1,793	3,244	1,793	3,532	1,931	3,507	1,894
2005-2034	3,113	1,816	2,982	1,793	3,270	2,177	3,459	2,921
2035-2064	2,705	1,671	2,798	1,674	3,245	1,553	3,457	2,253
2070-2099	1,793	822	2,422	1,698	2,705	1,465	3,150	1,789

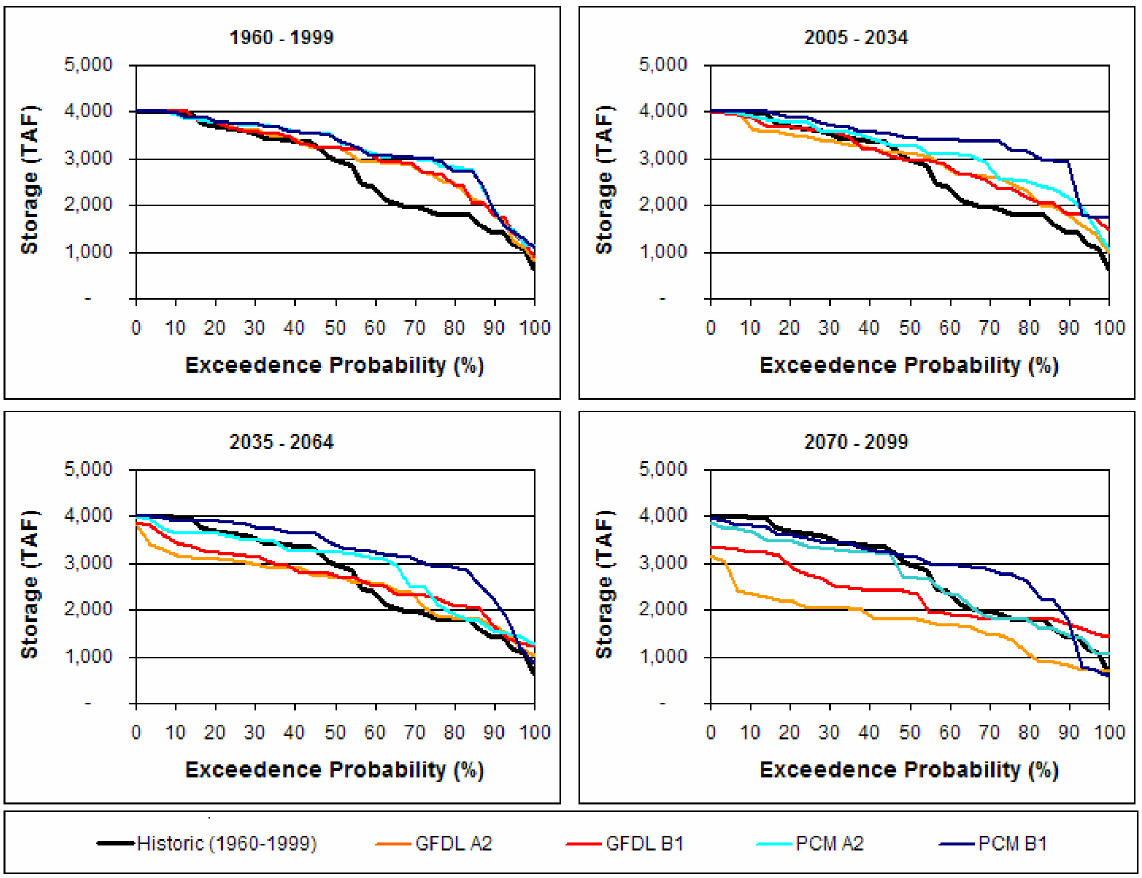


Figure 14. End-of-September Shasta storage

4.4.1.2. Surface water deliveries

Surface water deliveries to agriculture from the Feather and Sacramento Rivers are summarized in Figures 15 and 16 and Table 6. The model logic made in allocating surface water to agriculture is that all M&I and environmental water needs in a given time step are satisfied before surface water is allocated to agriculture. These results show a trend of increasing surface water diversions with time for all scenarios. The increases in deliveries were likely driven by increasing crop water demands, as summer temperatures increased for all scenarios with time. Similar to the changes in summer temperatures, increases in diversions were more pronounced for the two GFDL model runs. Interestingly, for the warmest and driest scenario, GFDL A2, there were years at the end of century when surface water deliveries were much lower than the other scenarios (exceedance probabilities above 75%), despite higher crop water demand. In these years, the GFDL A2 scenario could not deliver as much water to agriculture because there was insufficient storage in Shasta and Oroville.

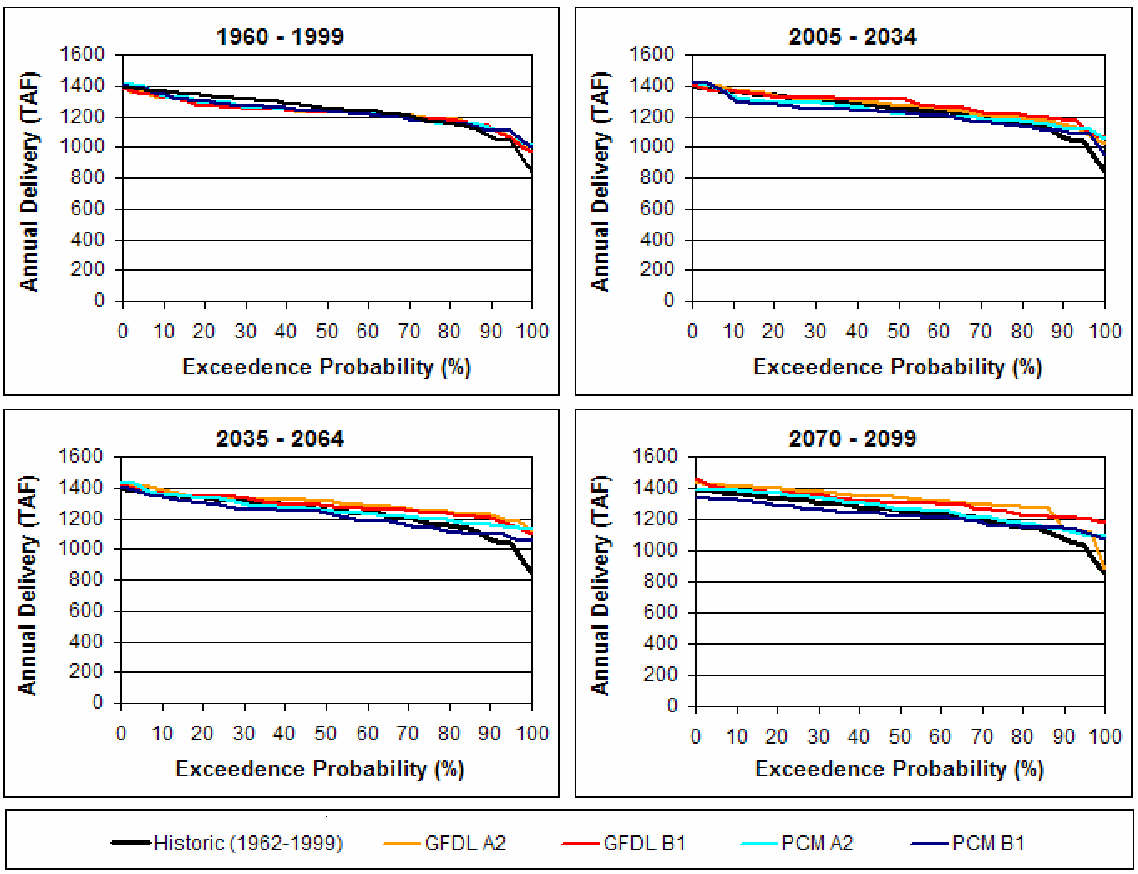


Figure 15. Agricultural surface water deliveries from the Feather River

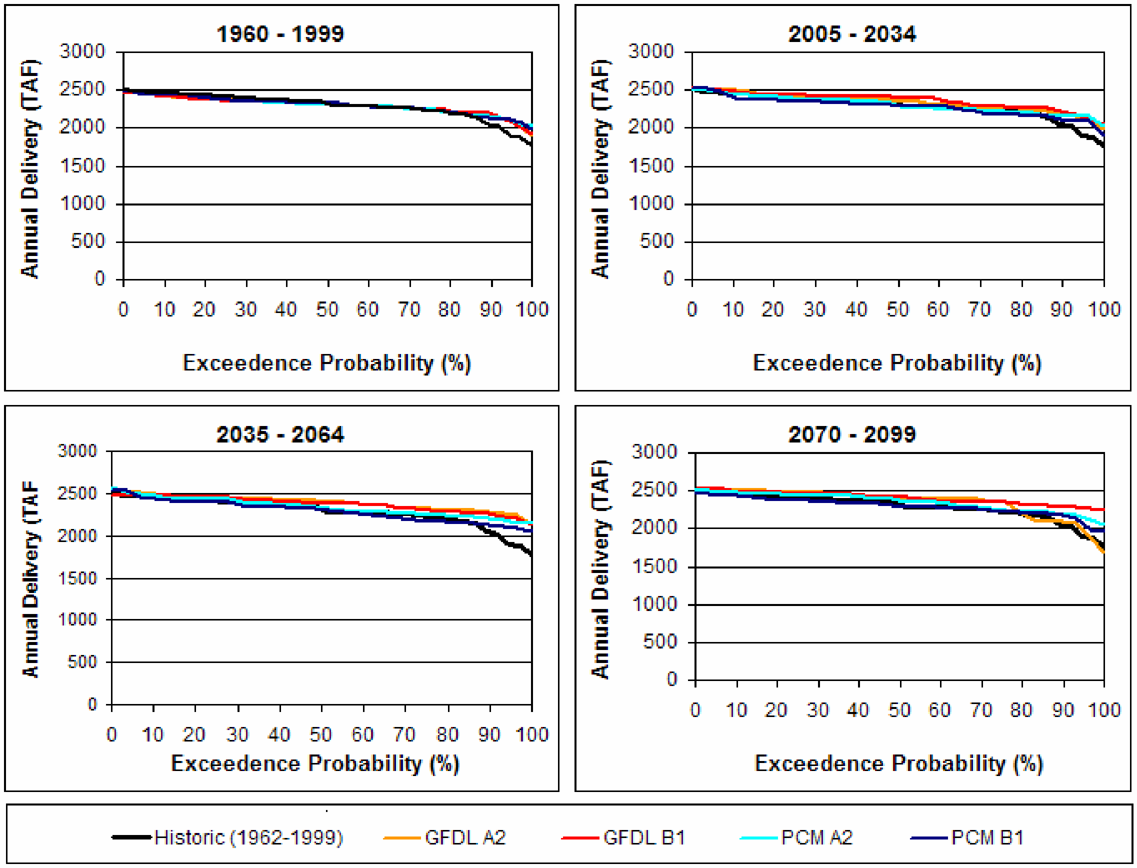


Figure 16. Agricultural surface water deliveries from the Sacramento River

Table 6. Average annual surface water deliveries: Sacramento Valley agriculture

	GFDL A2			GFDL B1			PCM A2			PCM B1		
	Average Annual Delivery (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Delivery (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Delivery (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Delivery (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)
1960-1999	3,537	0	0%	3,535	0	0%	3,523	0	0%	3,521	0	0%
2005-2034	3,613	77	2%	3,636	101	3%	3,568	44	1%	3,515	-6	0%
2035-2064	3,696	160	5%	3,672	137	4%	3,595	72	2%	3,517	-4	0%
2070-2099	3,672	136	4%	3,719	184	5%	3,624	100	3%	3,533	12	0%

4.4.1.3. Groundwater pumping

Annual groundwater pumping for the agricultural areas serviced by the Feather and Sacramento Rivers are summarized in Figures 17 and 18 and Table 7. References to annual deliveries in these graphics refer to the annual level of groundwater pumping. The model logic stipulates that areas with access to both surface water and groundwater will rely on available surface water supplies and shift to groundwater in times of scarcity. For both regions, groundwater pumping was relatively stable for all scenarios for the periods covering 1960 to 2064. In the last period, 2070–2099, pumping increased significantly in dry years (exceedance probabilities less than 30%) for the GFDL A2 scenario, when surface water deliveries were less reliable. Oddly, the wettest scenario, PCM B1, also showed a pronounced increase in groundwater pumping in dry years. This increase, however, was due to a sequence of dry years from 2073 through 2077, which resulted in substantial depletion of reservoir storage in Oroville and Shasta.

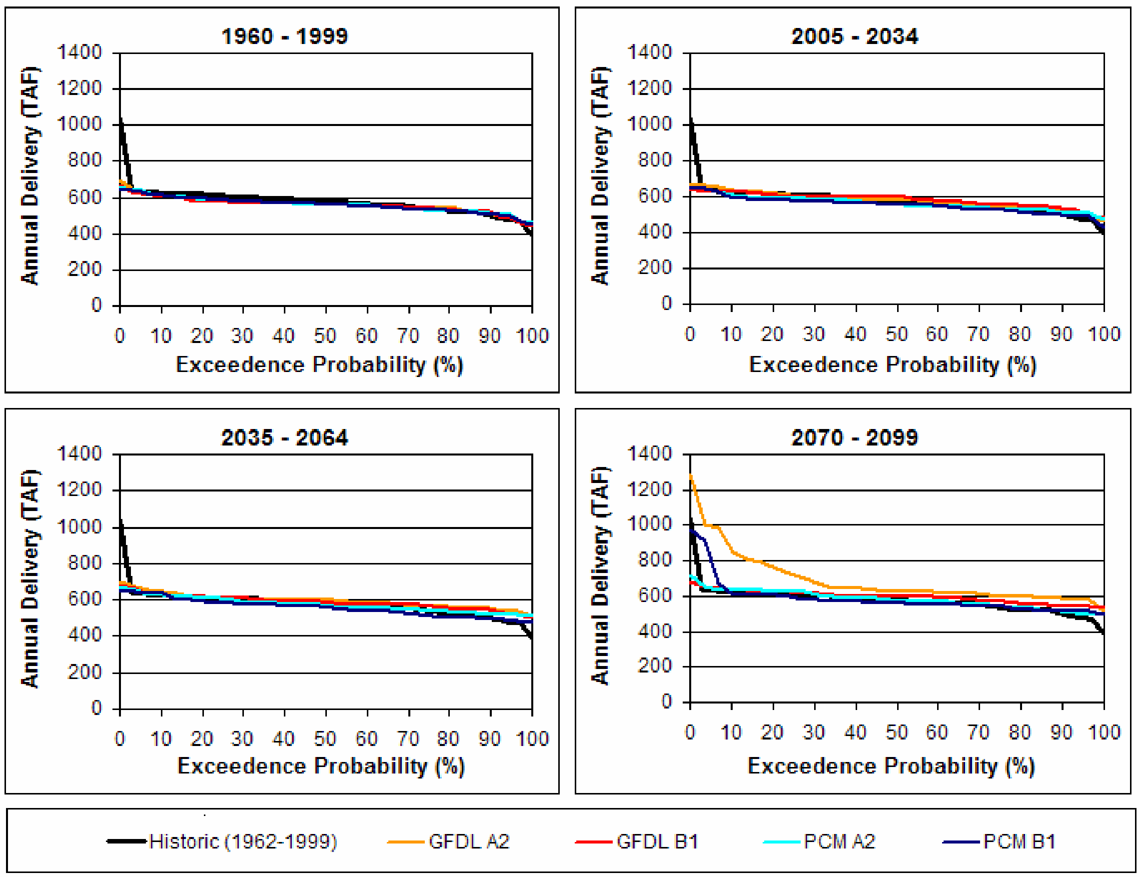


Figure 17. Groundwater pumping for Feather River agriculture

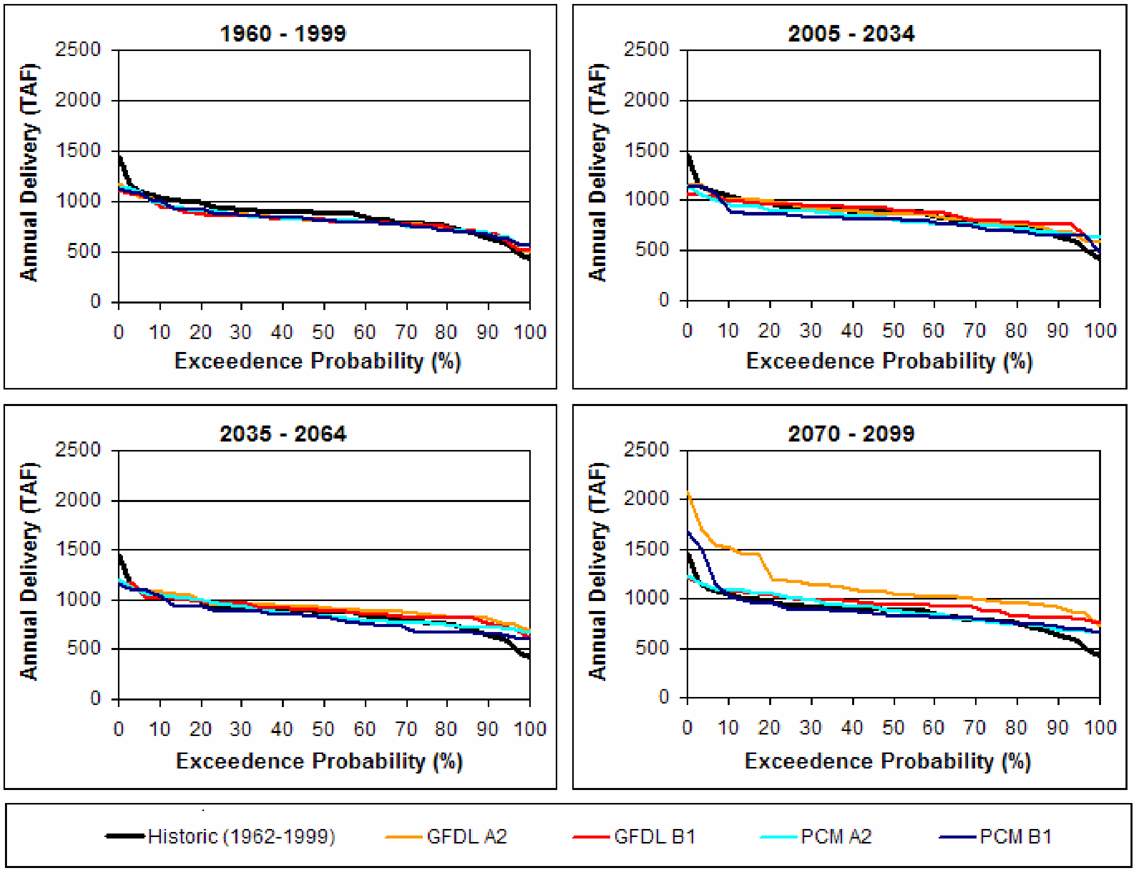


Figure 18. Groundwater pumping for Sacramento River agriculture

Table 7. Average annual groundwater pumping: Sacramento Valley agriculture

	GFDL A2			GFDL B1			PCM A2			PCM B1		
	Average Annual Delivery (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Delivery (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Delivery (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)	Average Annual Delivery (TAF)	Difference from 1960-1999 (TAF)	Difference from 1960-1999 (%)
1960-1999	1,379	0	0%	1,372	0	0%	1,382	0	0%	1,380	0	0%
2005-2034	1,443	64	5%	1,464	91	7%	1,386	4	0%	1,355	-26	-2%
2035-2064	1,517	138	10%	1,484	111	8%	1,440	58	4%	1,374	-7	0%
2070-2099	1,831	452	33%	1,545	173	13%	1,473	91	7%	1,477	96	7%

4.4.1.4. Groundwater levels

Average depth to the water table is presented for the Butte Basin and the Colusa Basin in Figures 19 and 20. Both aquifers showed relatively stable fluctuations around a mean for most of the period between 1960 and 2070. Recall that during this period the surface water deliveries were increasing with growing crop water requirements, such that groundwater pumping levels were only marginally increased. During the final period of analysis (2070–2099), however, an extended ten-year drought in the GFDL A2 scenario shifted agricultural water supplies to groundwater. As a result, groundwater levels decreased sharply.

The reader should recall that agricultural demands for these simulations were based on a fixed cropping distribution. It is conceivable that shifting cropping patterns as a result of surface water scarcity and groundwater drawdown would mitigate some of this effect. This will be explored in more detail in a later section.

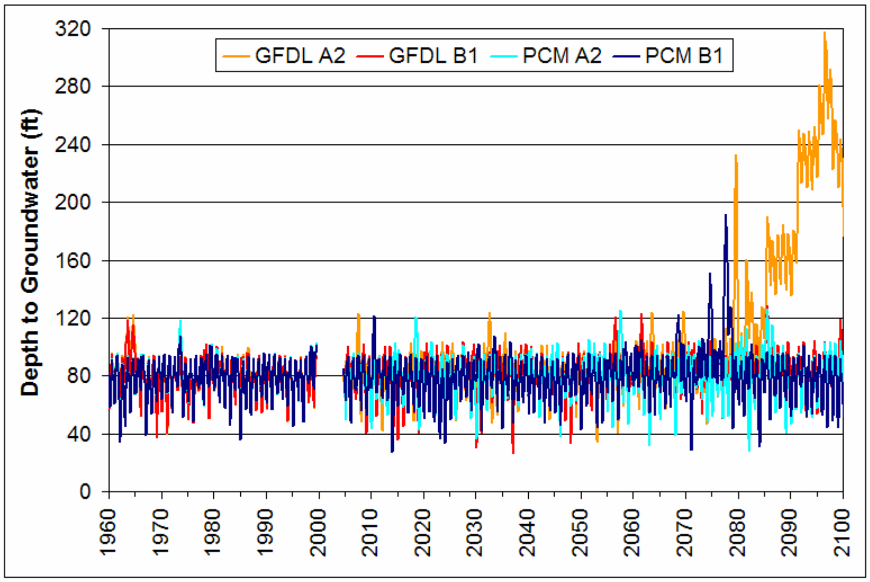


Figure 19. Changes in groundwater depth for the Butte Basin

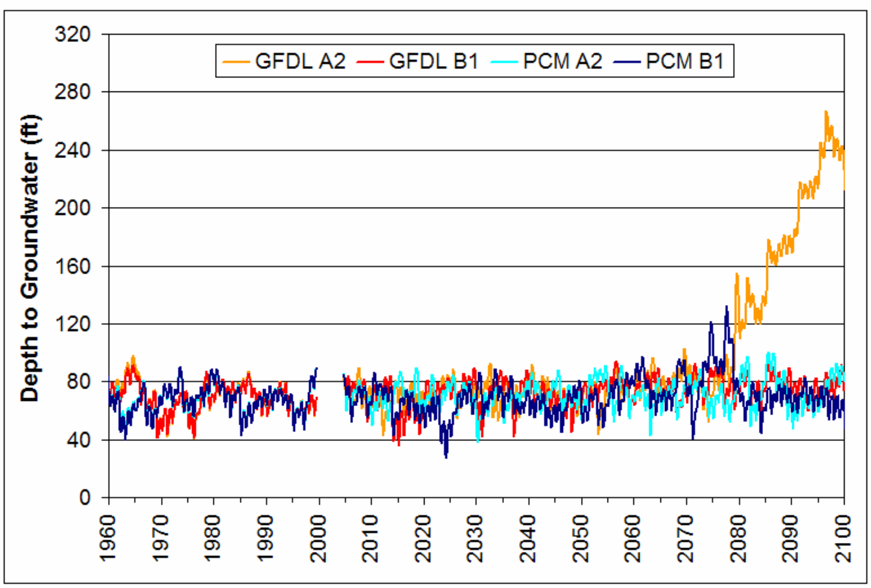


Figure 20. Changes in groundwater depth for the Colusa Basin

4.4.2. Stone Corral HUC

Water user districts in the Stone Corral HUC account for over 40 percent of CVP water contracts in the Sacramento Valley. The Stone Corral HUC also contains the two largest districts in the two broad categories that define CVP agricultural contractors: settlement contractors and agricultural services contractors. These two classes of contracts are distinguished by their allocation priority, with settlement contractors having senior water rights. The spatial disaggregation described in Section 3.1 allows us to consider the effects of climate change on these separate classes of contractors.

The following analysis presents results for the Glenn-Colusa Irrigation District (GCID) and the Tehama-Colusa Canal Authority (TCCA), which are the two largest contractors in their respective classes. GCID contracts a total of 825 thousand acre-feet (TAF) of water per year from the CVP and TCCA's annual water contracts from the CVP total 285 TAF. At present, these are the only water contracts constraining deliveries to agricultural areas. Results are shown only for the GFDL A2 scenario for the periods covering the middle and end of the 21st century, because this was where the impacts of climate change on water supply and delivery were the most pronounced.

4.4.2.1. Surface water deliveries

Surface water deliveries to GCID and TCCA are presented in Figures 21 and 22. The first thing to note is that neither district ever delivers its full contract amount. For GCID, this is because its contracts exceed the crop water requirements calculated by WEAP. In TCCA's case, it is likely due to the manner in which its contracts were distributed monthly over the growing season. This analysis assumed that the fraction of the annual contract that can be delivered in any month followed the same distribution that is used in the joint USBR-DWR planning model, CalSim-II. If this distribution was out of phase with the pattern of crop water demands over the growing season, then total deliveries would not have reached total contract amounts, because contracts were binding only in months of peak crop water demand.

Both districts had higher deliveries during the final period, 2070–2099, during wet-to-normal years, because sufficient water was available to satisfy the increased crop water demands. Surface water diversions to both districts were impaired in dry years due to water scarcity. However, TCCA experienced a more pronounced decline in delivery reliability, because its allocation priority was secondary to deliveries to settlement contractors.

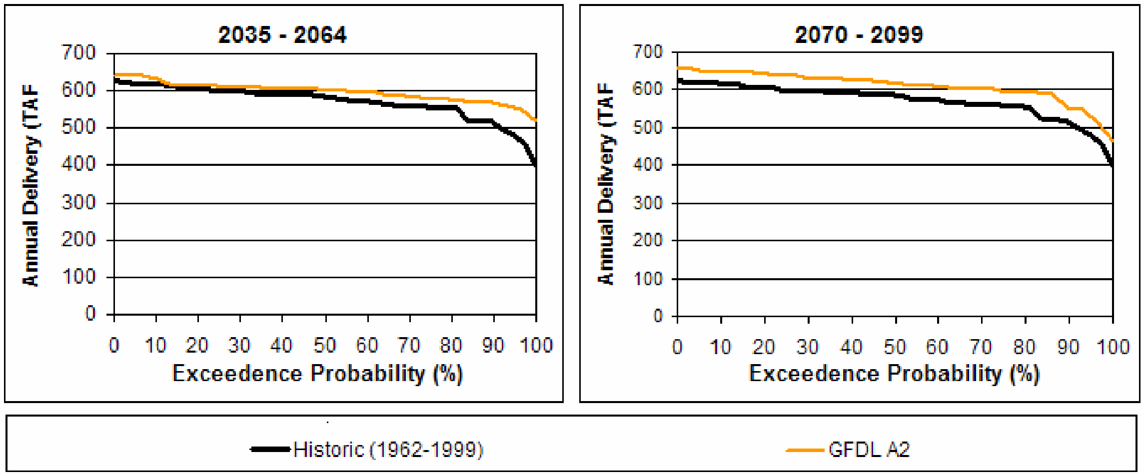


Figure 21. Annual diversions—Glenn-Colusa Canal

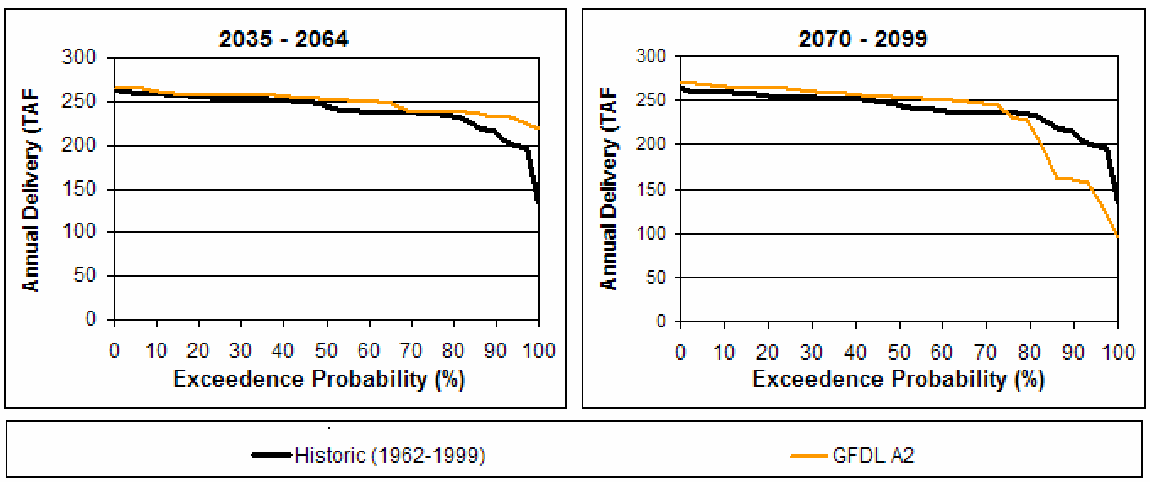


Figure 22. Annual diversions—Tehama-Colusa Canal

4.4.2.2. Groundwater pumping

Annual groundwater pumping for both GCID and TCCA are shown in Figures 23 and 24. Both districts showed the greatest groundwater pumping during the last period of analysis. Consistent with the previous set of graphs, GCID was able to satisfy its crop water demands for most years with surface water supplies and only relied on groundwater pumping in the driest years. TCCA, on the other hand, had a base level of groundwater pumping that was stable for most years, but increased sharply in dry years when river diversions were significantly reduced.

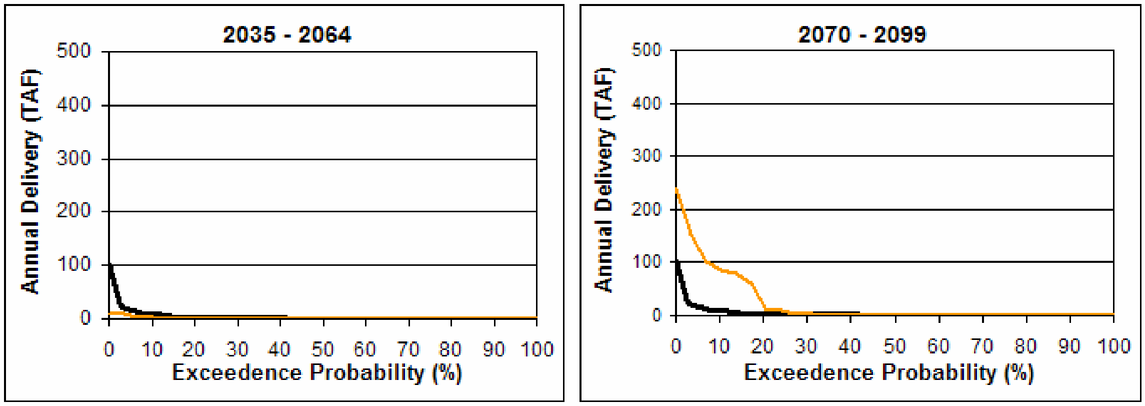


Figure 23. Annual groundwater pumping—Glenn-Colusa Irrigation District

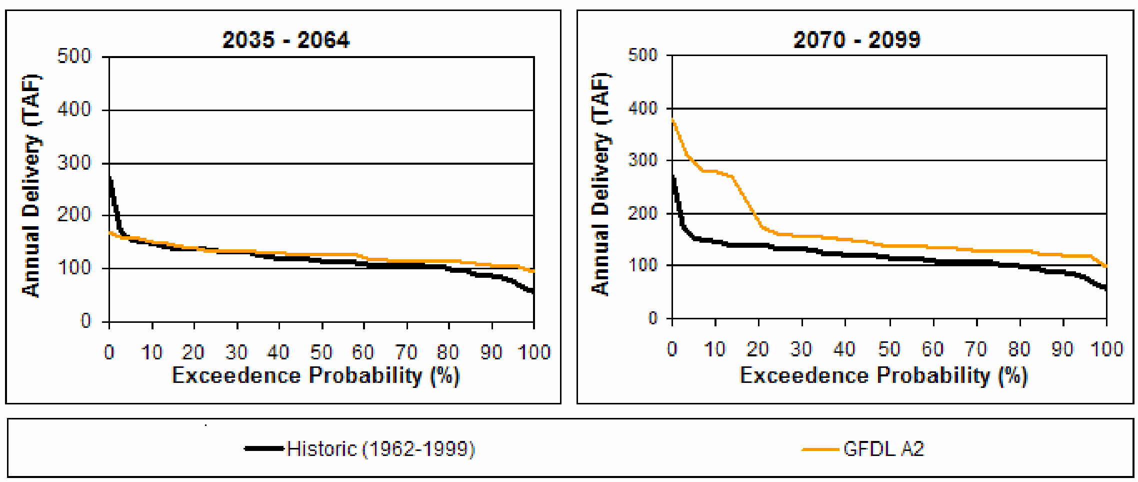


Figure 24. Annual groundwater pumping—Tehama-Colusa Canal Authority

4.5. Operations Analysis with Adaptation

The previous section outlined the impacts of climate change on agriculture in the Sacramento Valley under the assumption that cropping patterns and irrigation technology remain unchanged over the duration of a 100-year simulation. Under certain scenarios there was increased water scarcity at the end of the century that resulted in sharp decreases in surface water deliveries and increases in groundwater pumping. In the case of the GFDL A2 scenario, this impact was reflected in significant simulated declines in water table elevations throughout the valley towards the end of the 21st century.

This section describes how adaptation strategies may mitigate the impacts of climate change. Improved irrigation efficiency and changes in cropping patterns in response to water supply conditions were implemented in the model as described in Section 3.2 and Appendix B. The first part of the current section shows how these changes affect water supply requirements for several regions of the previously aggregated Stone Corral HUC. This discussion is followed by an assessment of predicted climate change impacts on agriculture in the Sacramento Valley when adaptation is simulated.

To facilitate the presentation of results, attention will focus on the climate change scenario that showed the largest impact on water resources in the Sacramento Basin, GFDL A2. Simulations were focused on the years 2050 to 2100, because this was the driest and warmest period of the scenario.

4.5.1. Water supply requirements with adaptation

The following analysis presents results for three future alternatives: a simulation without adaptation, a simulation with increases in irrigation efficiency, and a simulation with improved irrigation efficiency and shifts in cropping patterns related to the simulated status of available water supplies. Where adaptations were in place, it was anticipated that the overall water requirements for irrigation would be reduced through improvements in irrigation efficiency and shifting of farmland to less water-intensive crops in times of reduced water supply. In investigating the impact of adaptation strategies, model results for three of the regions created out of the disaggregation of Stone Corral HUC were considered: TCCA South (A2), GCID (B), and Non-District Users North (F3). Appendix A provides greater detail in the classification of these subunits.

For the purposes of this study, it was assumed that external regulatory pressures motivated irrigation districts to improve irrigation efficiency without regard to future climatic conditions. These improvements in irrigation efficiency were phased in gradually throughout the first 50 years of the 21st century and reached a maximum in 2050, after which efficiencies remained constant. Figures 25 through 27 show the effects of increased irrigation efficiency in terms of water supply requirements for the three regions mentioned above. Each graph shows the following:

- The 2050–2100 base supply requirement without changes in irrigation efficiency (Base, blue)
- An average of the same supply requirement covering the first and last 25 years in the period (BaseAveragebyperiod, green), which shows how supply requirements increase in the advent of the “mega-drought” occurring at the end of the 21st century
- The 2050–2100 supply requirement with changes in irrigation efficiency (Irrigation Efficiency, red)
- Its associated average for the first 25 and last 25 years in the time period (IrrEffAveragebyperiod, cyan)
- The average historic (1962–1998) supply requirement as a reference

The results show a decline in supply requirements as improvements in irrigation efficiency are implemented. However, these changes are not consistent across the different regions. GCID, for example, experiences a relatively small decline in supply requirement when compared with Non-district Users North (F3) due primarily to differences in crop patterns. While almost 75% of the irrigated land in GCID is planted to rice, a crop with little potential for improved irrigation technology because it relies upon flooded fields, Non-district Users North has almost 50% of land in cereals and pasture, two crops with high potential for improvements in irrigation technology.

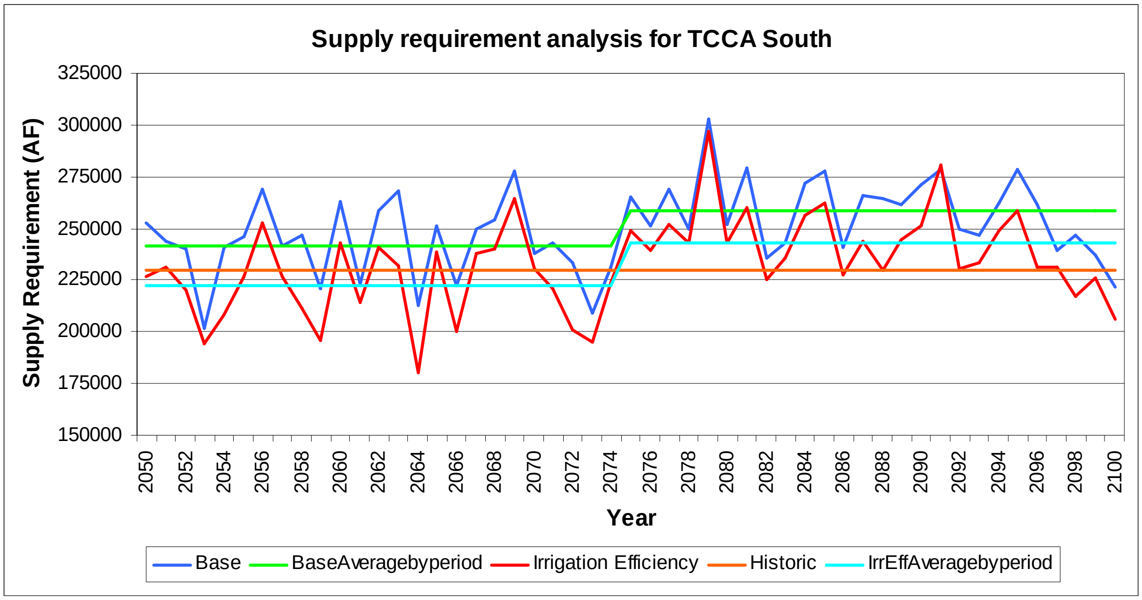


Figure 25. Changes in supply requirement associated with improvements in irrigation technology—TCCA South

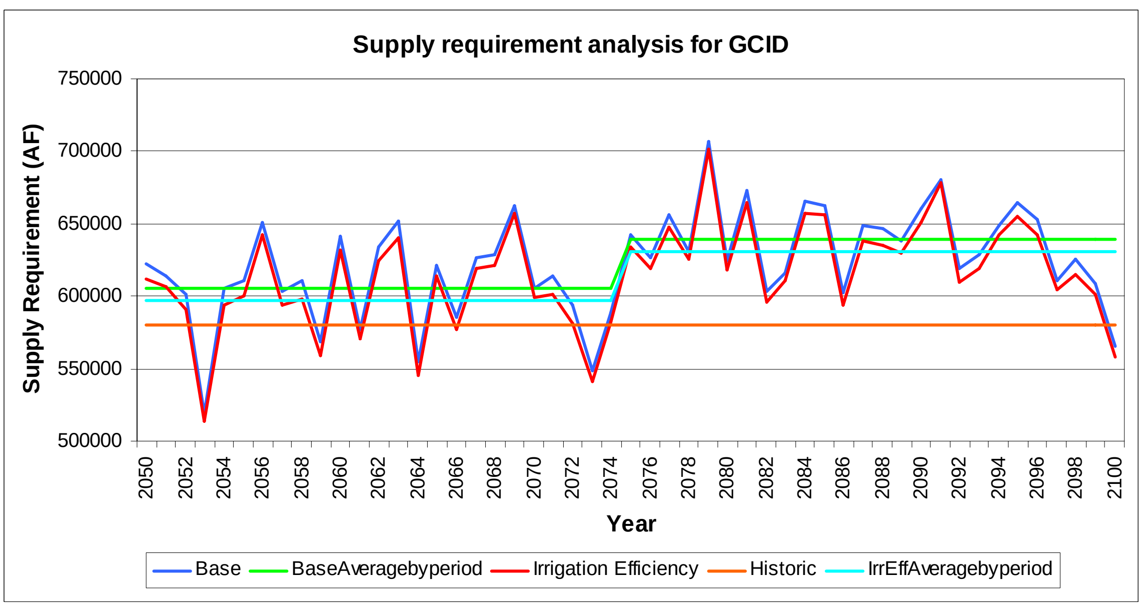


Figure 26. Changes in supply requirement associated with improvements in irrigation technology—GCID

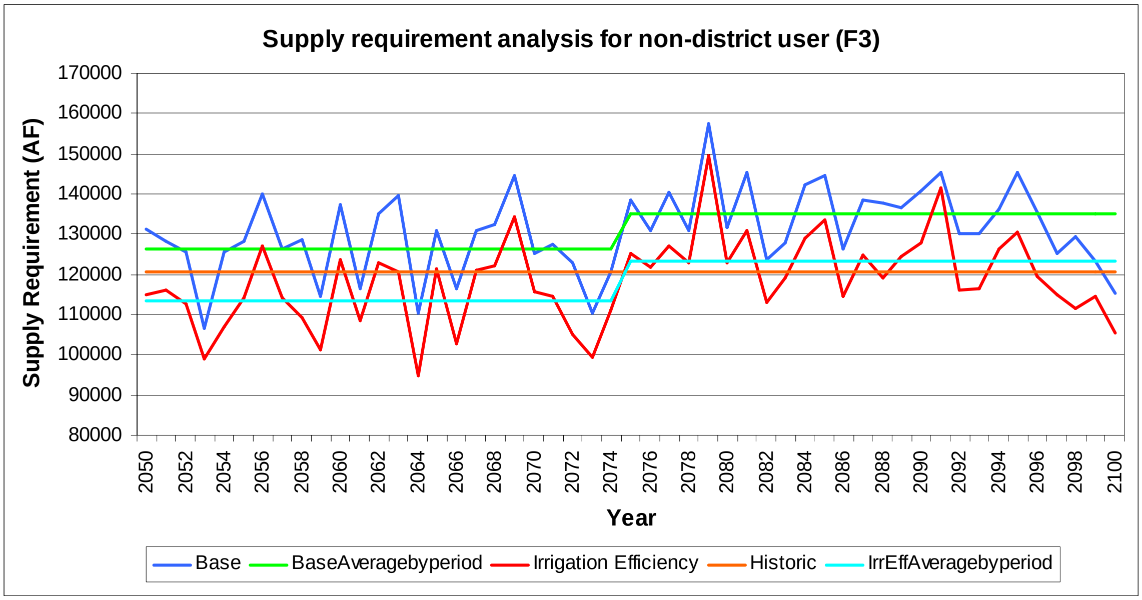


Figure 27. Changes in supply requirement associated with improvements in irrigation technology—Non-district Users North

In addition to improvements in irrigation technology, another potential adaptation to climate change would involve adjusting cropping patterns as a function of the evolving status of available water supplies. This adaptation reflects the fact that at the beginning of the growing season, farmers decide which crops to plant based on anticipated surface water supplies and groundwater levels. How farmers respond to these changing conditions is a function of a number of factors, which change depending on the reliability of various available water sources. For example, non-district areas base their cropping decisions solely on the depth to groundwater, because they lack guaranteed surface water supplies. As a CVP settlement contractor, GCID changes cropping decisions only when inflows to Lake Shasta reach a critical level (i.e., less than 3.4 million acre-feet), at which time its allocations are reduced by 25%. The TCCA South region, composed of CVP agricultural services contractors, suffers cuts to its allocations based on both the predicted inflows into Shasta and also the current reservoir storage levels.

The implication is that indexes of available supply must be calculated for each year in order to permit the various types of water user to make appropriate cropping decisions. Based on the value of these supply indexes, a multinomial logit model of cropping shares, estimated from historical data, is employed to determine the distribution of crops and fallow land in that year for the given user. These logit equations and the details of their estimation are described in detail in Appendix B, along with the formulas used to define the evolving water supply indices. The structure and coefficients of these various expressions have been programmed into WEAP so that at the start of every cropping season over the course of the 21st century, an adaptive simulated cropping pattern can be defined.

The implications of these shifts in cropping pattern are shown in Figure 28. Crop shares for the three regions are analyzed at two different points in time: 2050 and 2092 for the GFDL A2 climate scenario.[6] The 2092 period coincided with the end-of-century mega-drought included in that scenario. Regions such as TCCA South, with weak entitlements and variable allocations, shifted their crop patterns under a very dry condition by increasing land fallowing and decreasing the share of irrigated crops. Users with more reliable water supplies, such as GCID, maintained more constant crop shares. Finally, users relying solely on groundwater pumping showed very little change in crop patterns. This was due to the low sensitivity to the depth to groundwater of overall crop decisions that emerged from the econometric analysis (see Appendix B).

The combined effect of improved irrigation efficiency and a dynamic crop pattern based on dynamic simulated water supply and groundwater conditions is a decline in water supply requirements during the period of analysis. This can be seen by examining Figures 29 through 31, which are comparable to Figures 25 through 27, but which include a dynamic crop-share decision. The effect of changing cropping patterns is reflected in the difference between these two sets of graphs. These differences are summarized in Table 8.

Table 8. Summary comparisons between Figures 25–27 and 29–31

		User		
Scenario	**Period**	**TCCA South**	**GCID**	**Non District North**
Hist	1962-1998	230	580	121
Base (no adaptation)	2050-2074	242	606	126
	2075-2099	259	639	135
Irrigation Efficiency	2050-2074	222	597	113
	2075-2099	243	631	123
Irrigation Efficiency and Dynamic Crop	2050-2074	224	587	114
	2075-2099	235	616	124

Units: TAF (thousand acre-feet)

6 The implications of the changes in water supply and cropping pattern for farm costs, revenues, and profits in the Sacramento Valley are evaluated separately from WEAP in a post-processing module and will be reported in a separate memorandum.

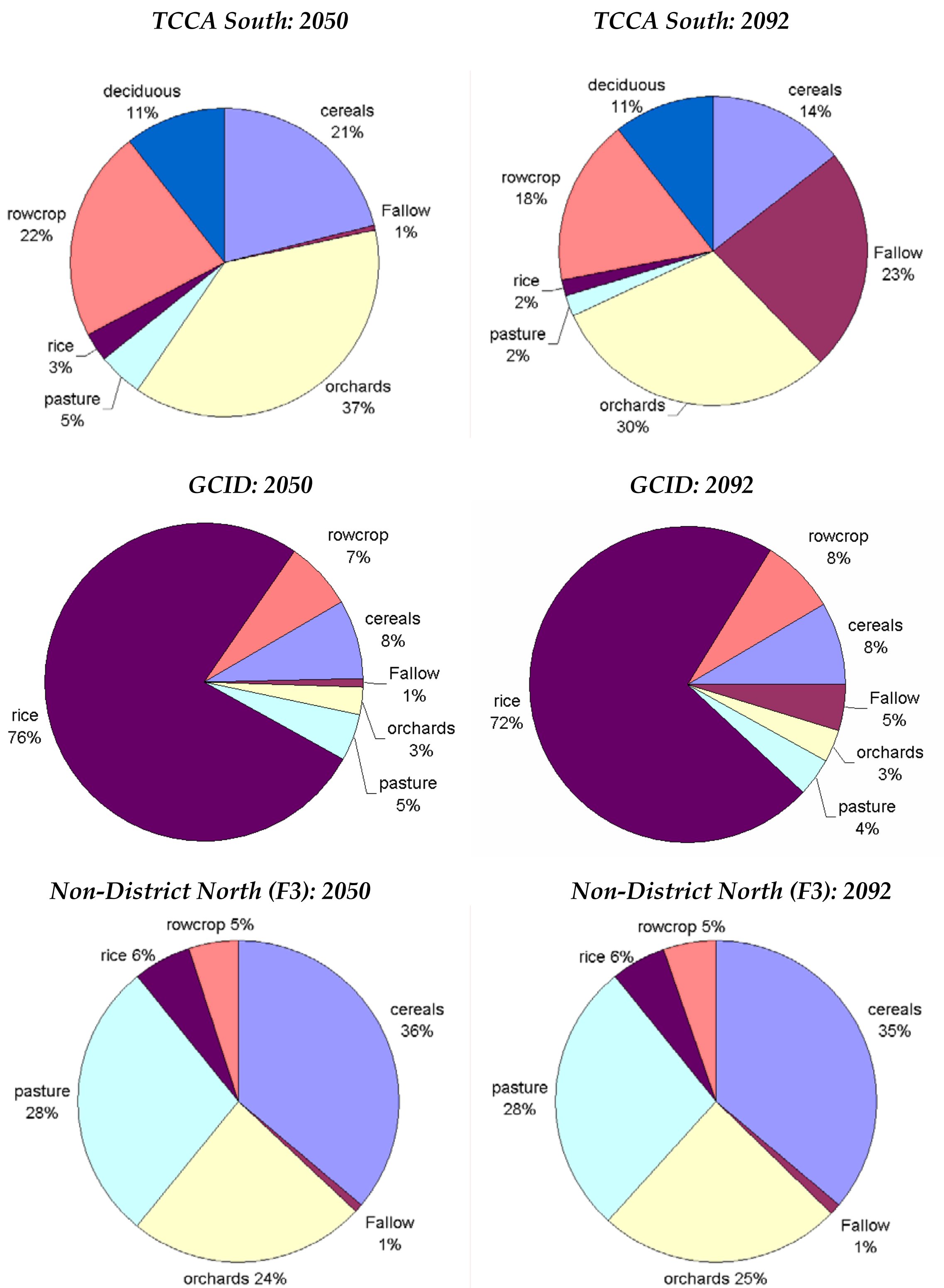


Figure 28. Simulated changes in cropping patterns for three regions of the Sacramento Valley between 2050 and 2092 under the GFDL A2 climate scenario

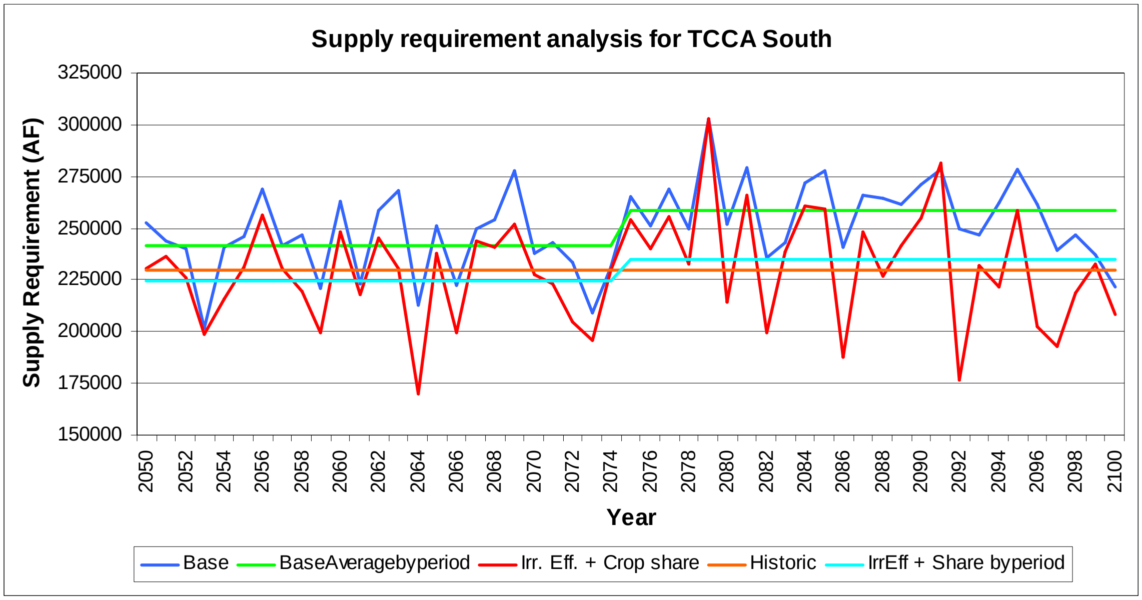


Figure 29. Changes in supply requirement associated with improvements in irrigation technology and dynamic cropping patterns—TCCA South

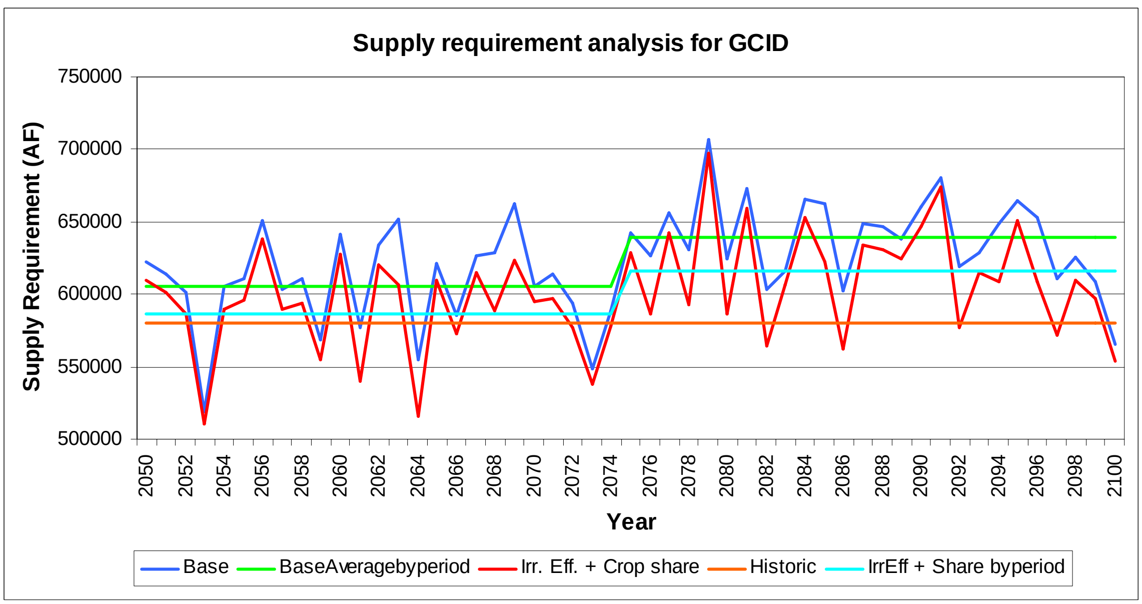


Figure 30. Changes in supply requirement associated with improvements in irrigation technology and dynamic cropping patterns—GCID

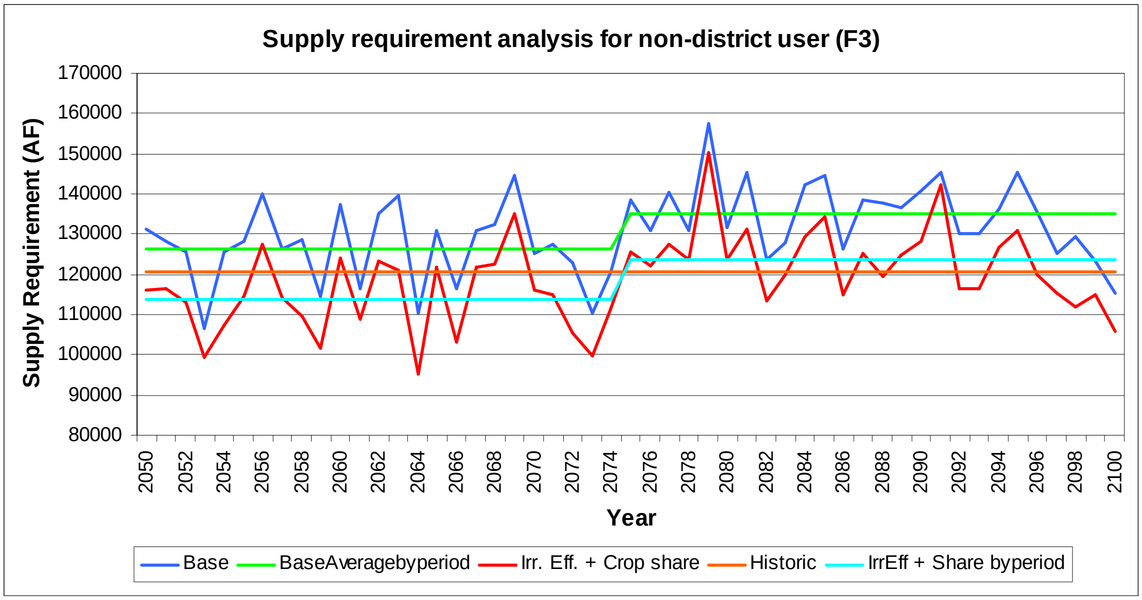


Figure 31. Changes in supply requirement associated with improvements in irrigation technology and dynamic cropping patterns—Non-District Users North

4.5.2. Water supply and delivery

The previous section showed that adaptation strategies have varying impacts at the irrigation district level depending upon water rights and the type of crops grown within districts. In general, improvements in irrigation efficiency were most effective in reducing crop water demands in districts that did not plant a large portion of their land in rice, which was not a targeted crop for irrigation technology advancement due to its need for ponded water over extended periods of the growing season. Fallowing agricultural land in dry years also achieved substantial water savings, but had the biggest impact in districts that were most susceptible to reduced surface water deliveries (i.e., CVP agricultural contractors). The combined effect of both adaptation strategies showed that in the driest years some districts could reduce irrigation requirements by 20 to 30 percent.

This section focuses on the cumulative effect of implementing adaptation strategies more broadly throughout the Sacramento Valley. The analysis presents WEAP simulations for each of the climate change scenarios with both adaptation strategies implemented across all agricultural areas of the Sacramento Valley. These simulations suggested that increasing temperatures and declining precipitation result in patterns of agricultural water supply and delivery similar to those seen in Section 4.4. Adaptation strategies reduced the absolute effect, but the relative impacts between scenarios and with time remained the same. As such, graphics of the “with adaptation” simulations corresponding to Figures 13 through 22 would look very similar to those associated with the “without adaptation” simulations, with only the values on the y-axes changing significantly. For this reason, Table 9 compares the impacts of simulations run with and without adaptation for only the driest and warmest future period (2070 to 2099).

Table 9. Water supply and delivery (2070–2099): with and without adaptation

	GFDL A2			GFDL B1			PCM A2			PCM B1		
	Without adaptation	With adaptation	Difference	Without adaptation	With adaptation	Difference	Without adaptation	With adaptation	Difference	Without adaptation	With adaptation	Difference
Average Annual Agricultural Water Requirement (TAF)	5,658	4,856	802 (-14%)	5,348	4,612	735 (-14%)	5,188	4,502	687 (-13%)	5,107	4,339	768 (-15%)
Average Annual Agricultural Deliveries (TAF)	3,672	3,279	393 (-11%)	3,719	3,301	418 (-11%)	3,624	3,230	393 (-11%)	3,533	3,124	409 (-12%)
Average Annual Groundwater Pumping to Agriculture (TAF)	1,831	1,550	281 (-15%)	1,545	1,328	217 (-14%)	1,473	1,262	211 (-14%)	1,477	1,230	247 (-17%)
Average Carryover Storage in Lake Shasta (TAF)	1,728	1,734	-6 (0%)	2,324	2,331	-7 (0%)	2,621	2,646	-25 (1%)	2,925	2,953	-28 (1%)
Average Carryover Storage in Lake Oroville (TAF)	1,641	1,647	-5 (0%)	2,032	2,044	-12 (1%)	2,275	2,296	-21 (1%)	2,475	2,503	-28 (1%)
Maximum Groundwater Drawdown in Stone-Corral (ft)	267	225	42 (-16%)	98	99	-1 (1%)	100	100	1 (-1%)	132	124	8 (-6%)
Average Annual Urban Deliveries (TAF)	381	499	-118 (31%)	393	507	-115 (29%)	391	506	-115 (29%)	389	505	-115 (30%)
Average Annual Delta Exports (TAF)	5,072	5,179	-107 (2%)	5,610	5,622	-13 (0%)	5,533	5,564	-31 (1%)	5,469	5,495	-26 (0%)

Improved irrigation efficiency and increased land fallowing in dry years resulted in substantial reductions in agricultural water supply requirements for all climate change scenarios. This, in turn, reduced the average annual surface water deliveries and groundwater pumping to agriculture. For the GFDL A2 scenario, which included a prolonged drought from 2085 through 2095, the reduced reliance on groundwater caused a less pronounced decline in groundwater levels. However, even with adaptation in place, total water table drawdown for this scenario was still much greater than that simulated in each of the other scenarios. For all scenarios, the reductions in crop water demands meant that irrigation districts were able to satisfy a higher proportion of their irrigation requirements.

Despite the large decrease in agricultural demands, CVP and SWP reservoirs showed little change in their operation as a result of implementing adaptation strategies. Carryover storage levels in both Lake Shasta and Lake Oroville were only 0 to 1 percent higher than they were when no adaptation was in place. This suggests that other water users in the basin captured the water savings realized as a consequence of reducing consumptive demands in agricultural areas. Table 8 shows that some of the additional water was shifted to Sacramento Valley urban areas and delta exporters. The remaining water was used to satisfy various environmental requirements.

In general, modification of agricultural demands as a result of implementing adaptation strategies to climate change improved the reliability of surface water deliveries for all water users in the basin. The volumes of the water savings and increased deliveries, however, varied considerably across the four climate change scenarios. The drier scenarios generally showed greater differences from simulations run without adaptation, because land fallowing occurred more frequently in these scenarios. The relative effect of adaptation (i.e., the percent difference), on the other hand, was consistent for all scenarios. Thus, while there is still considerable uncertainty associated with evaluating the absolute impacts of a forecasted climate, it is clear that mitigation measures undertaken in times of water scarcity will have similar impacts on the water supply condition, independent of climatic variability.

5.0 Conclusions

This study illuminates two very important conclusions. The first is that an integrated hydrology/water resource systems tool offers profound advantages when it comes to investigating climate change impacts and adaptations in the water sector. Unlike CalSim-II and CALVIN, the WEAP framework is able to directly evaluate future climate scenarios without relying on a perturbation of the historic patterns of hydrology that were observed in the past. In addition, potential increases in water demand associated with higher temperatures and lower rainfall are included in the analysis in a more robust manner than with the other tools.

Second, water management adaptation in the water resources sector has the potential to mitigate the impacts of climate change. Improvements in irrigation efficiency and shifts in cropping patterns can reduce the demand in the agricultural sector and free up water for other purposes. These adaptations may prevent serious over-exploitation of system groundwater in the coming decades.

6.0 Future Steps

While the use of the Sacramento Valley WEAP application as part of the current investigation demonstrates some of the advantages of using an integrated hydrology/water management framework for climate change impact and adaptation analysis, it also reveals several avenues for additional activity which would deepen our understanding the implications of climate change for water management in California. Some potential useful future steps include the following:

Further disaggregating the Sacramento Valley floor. To fully explore the adaptation potential of agricultural water users in the Sacramento Valley, the disaggregation process must extend beyond the Stone Corral HUC.

Expanding the model to include the San Joaquin Valley. Climate change will impact the hydrology and water management decisions in the San Joaquin Valley. This has implications for Delta inflows and exports that need to be considered.

Expanding the model to include the Southern California coastal zone. Future demand patterns in the Southern California coastal zone, which may be sensitive to climate change, will be a key water management driver in the coming century. This zone needs to be dynamically integrated into the model and available for the development of adaptation strategies.

Using ensembles of future climate scenarios. The current analysis relies upon four distinct realizations of the GCM/emission scenario combinations that have been downscaled into four future climate time series for California. The WEAP mode can be run repeatedly under a range of climate realizations, which should allow for a more robust analysis of risk.

Implementing a market for water. Agricultural water users may fallow additional land during dry periods in order to supply water to meet M&I demand. Programming WEAP to allow for this possibility would illuminate a potentially promising adaptation.

Introducing Delta salinity standards into the model. If the model is to be successfully integrated with the San Joaquin Valley and the export zone, then a better representation of the Delta salinity standards would be beneficial.

Adjusting the land cover distribution in the upper watershed as a function of climate scenarios. Models of evolving land class as a function of future climate have been developed in companion papers of this investigation (Battles et al. 2006; Lenihan et al. 2006). Simulating the impact of these changes on the hydrology would be a very interesting exercise.

Adjusting the ET routine to allow CO_2 modifications. There is some thought that increased CO_2 concentrations may change the energy balance in ways that require modifications to our current methods of calculating ET. These changes could be accommodated in the WEAP hydrology module.

Introducing dynamic ecosystem objectives, including temperature-based objectives. Little has been said about ecosystem objectives in this study, as they are expressed as static instream flow requirements. It would be interesting to program dynamic ecosystem objectives that track the recent conditions in the system and set flow standards based on the evolving needs of the system. This could include standards that are driven by the need to maintain certain temperatures (WEAP includes a simple water temperature routine).

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8.0 Glossary

A2	A future emissions scenario with relatively high greenhouse gas emissions as detailed in the IPCC SRES
B1	A future emissions scenario with relatively low greenhouse gas emissions as detailed in the IPCC SRES
CalSim-II	Planning model of California's State Water Project (SWP) and the federal Central Valley Project (CVP), developed jointly by the California Department of Water Resources (DWR) and U.S. Bureau of Reclamation (USBR)
CALVIN	California-wide economic-engineering optimization model for water supply and environmental purposes developed at the University of California.
CCCC	California Climate Change Center
CVP	Central Valley Project
DSS	Decision support system
DWR	California Department of Water Resources
ET	Evapotranspiration
GCM	General circulation model
GFDL	A GCM developed by the Geophysical Fluid Dynamics Laboratory
IPCC	Intergovernmental Panel on Climate Change
M&I	Municipal and industrial
NAAG	National Agriculture Assessment Group
NCAR	National Center for Atmospheric Research
NHI	Natural Heritage Institute
NWAG	National Water Assessment Group
PCM	Parallel climate model, a GCM developed by the National Center for Atmospheric Research
SEI	Stockholm Environment Institute
SRES	Special Report on Emissions Scenarios, published by the IPCC
SWP	State Water Project (of California)
TAF	Thousand acre-feet, a unit of volume.
USBR	United States Bureau of Reclamation

USGS	United States Geological Survey
VIC	Variable Infiltration Capacity model, a macroscale hydrologic model developed at the University of Washington that solves full water and energy balances.
WEAP	Water evaluation and planning simulation model developed by the Stockholm Environment Institute

Appendix A:

Disaggregation of Stone Corral HUC

A.1. Disaggregation Approach

The disaggregation process entails the creation of new nodes for what used to be just the Stone Corral node. Each of the new nodes represents the small catchment associated with a group of water users (districts). Associated with each node are links representing water sources and water return flows both to and from surface and groundwater sources/sinks. Considering the large number of distinctive users within this HUC, some of these users were grouped when their water supplies and crop patterns were similar. The grouping procedure started by gathering all available information on different criteria such as water supply (source and water right), crop pattern and geographic location for each one of the users in the HUC and defining different categories for each. The different criteria were prioritized as shown in Table A-1. Finally all users where sorted into different categories according to the tiered system defined by the different criteria levels, starting with Level 1 and continuing through each subsequent level. Table A-2 shows the final classification scheme and Table A-3 shows acres and crop patterns for these districts based on 1998 DWR GIS land survey's data.

Table A-1. Criteria used in aggregation of different users

Level	Criteria
1	Water user type: district, non-district, and native vegetation (no irrigation).
2	Source of water: CVP contractors (settlement and non-settlement); Colusa Drainage users; Groundwater dependence or other source (e.g., Stony Creek).
3	Geographic location (proximity to Sacramento River): it was found that the proximity to the Sacramento River was a good proxy for crop patterns (rice, pasture), and soil type in some cases.
4	Cropping patterns: in those cases that proximity to Sacramento River was not a good proxy for crop patterns we used this final level of sorting.

Table A-2. Classification of water users in Stone Corral HUC (not including urban and refuges)

Level 1 **User type**	**Level 2** **Water source**	**Level 3** **Geographic location**	**Level 4** **Crop pattern**	**User**	**Code**
District	CVP Tehama-Colusa Canal	North region	Mostly cereal and orchard	GLIDE W.D.	A1
				KANAWHA W.D.	
				ORLAND-ARTOIS W.D.	
		South region	Mostly orchard, rowcrop and cereal	GLENN VALLEY W.D.	A2
				DAVIS W.D. (TC)	
				4-M W.D.*	
				DUNNIGAN W.D.	
				WESTSIDE W.D.	
				COLUSA COUNTY W.D.	
	CVP Tehama Colusa/Glenn Colusa/Settlement	N/A	Mostly rice	GLENN COLUSA I.D.	B
	CVP Settlement	Bank of Sacramento River	Mostly rice, rowcrop and oilcrop	ROBERTS DITCH CO.	C1
				PELGER M.W.C.	
				TISDALE I. & D.C. SERVICE AREA	
				ELIZABETH DOMMER/BARB KING	
				RIVER GARDEN FARMS CO.	
				MERIDIAN FARMS WATER CO.	
				SUTTER MUTUAL WATER COMPANY	

Level 1 User type	Level 2 Water source	Level 3 Geographic location	Level 4 Crop pattern	User	Code
				RECLAMATION DISTRICT 108	
				PRINCETON-CODORA-GLENN I.D.	
		Not in Bank	Mostly Rice	OLIVE PERCY DAVIS	C2
				MAXWELL I.D.	
				PROVIDENT I.D.	
	Stony Creek	N/A	N/A	ORLAND UNIT WATER USERS ASSN.	D
	Colusa Drainage	N/A	N/A	COLUSA DRAIN WATER USERS ASSOC	E
Non-District	Mix of surface and (riparian) and groundwater	Close to Sacramento River	Mostly rice and rowcrop	Users along Sac. R. (ND Sacramento River)	F1
	Mostly groundwater	Far from Sacramento River	Mostly rowcrop and cereal	Users between Colusa County and Glenn Colusa IDs (ND South)	F2
			Mostly cereal, pasture and oilcrop	Users between Orland Artois and GCID IDs (ND North)	F3
Native Vegetation+	N/A	N/A	N/A	N/A	G

Notes: N/A: Not applicable; + Does not include refuge.

Table A-3. Summary of data for users considered in disaggregated model

User		Water Sources	Total acreage (acres)	Land use type (%)													Total irrigated acreage (acres)
				cereals	deciduous	oilcrops	orchards	grasspasture	rangeland	rice	rowcrop	shrubs	Urban - imp	Urban - per	water	wetlands	
Tehama Colusa Canal Authority North	A1	TCCA + GW	54,348	31.9	0.0	3.3	24.8	9.4	9.2	8.3	4.9	0.3	3.3	1.6	2.3	0.8	44,879
Tehama Colusa Canal Authority South	A2	TCCA + GW	111,210	17.1	8.4	1.7	25.9	4.1	16.7	2.7	20.1	0.1	1.7	0.8	0.3	0.5	88,836
Glen Colusa ID	B	GCC + GW	170,998	5.6	0.0	0.9	2.3	3.7	3.9	61.3	5.8	0.0	2.4	1.2	1.8	11.0	136,099
Settlement Stone Corral close to Sac R.	C1	Sac R. + GW	146,161	10.9	0.0	15.4	2.6	1.7	2.4	37.4	25.7	0.0	1.0	0.5	1.8	0.6	136,851
Settlement Stone Corral far from Sac R.	C2	Sac R. + GW	30,689	0.2	0.0	2.1	0.1	1.0	0.3	80.7	2.1	0.0	1.7	0.9	5.2	5.7	26,451
Orland Water Unit Association	D	Stony Cr. + GW	11,148	5.2	0.0	0.0	20.4	35.3	15.6	0.0	0.2	0.0	15.0	7.5	0.6	0.1	6,805
Colusa Drain Users	E	Col. Drain + GW	27,694	7.3	0.0	5.2	0.2	4.0	2.2	56.4	15.3	0.0	1.4	0.7	1.9	5.4	24,487
Non District Sacramento River	F1	Sac R. + GW	175,232	9.1	0.3	5.9	11.3	2.5	4.6	40.1	12.4	0.2	2.0	1.0	3.8	6.7	143,021
Non District South	F2	GW	44,069	23.9	0.0	5.8	7.4	5.1	5.4	7.6	31.8	0.0	2.4	1.2	0.7	8.8	35,922
Non District North	F3	GW	49,214	26.5	0.0	3.0	19.9	22.2	10.5	4.6	4.2	0.1	4.9	2.4	1.0	0.8	39,569
Native	G	N/A	374,717	0.0	40.1	0.0	0.0	0.0	49.1	0.0	0.0	10.7	0.0	0.0	0.0	0.0	0

A.2. Calibration

The original (aggregated) WEAP model of the Sacramento Basin had undergone a process to calibrate its major physical and operational parameters. This calibration process resulted in a model that represented with reasonable accuracy physical processes such as streamflow runoff and ground water table levels as well as management decisions such as reservoir releases (Yates et al., 2005c). However in disaggregating the Stone Corral HUC it was deemed important not just that we have the overall water budgets correct (i.e., total precipitation, total runoff) but also that we have the right water allocation to the new sub-units of the former Stone Corral HUC, including the right balance between surface water and ground water utilization for each new sub-unit. A calibration was carried out on the "disaggregated" model using a procedure that considered the following objectives:

- Recreate regional scale water budget and streamflow and groundwater levels that were already represented with reasonable accuracy in the aggregated version of the model and also;
- Represent varying characteristics of water supplies for the different water users represented by the new model

As noted above, most of the water users in Stone Corral have access to both surface and groundwater. In order to accomplish the second calibration objective, it was crucial to determine the right allocation of water supplies for each district (user). In those cases where a user has more than one water source, WEAP uses a preference parameter to determine the order in which different sources are used. A source with a higher preference will be used until depleted (as determined by the competing demands for that given source) before a second source is drawn upon. This system does not literally represent reality because, although there could still be available water from a particular source of surface water, economic or institutional constraints can limit the amount of water obtained by a district from that source and favor a second source of water. One example of this would be water entitlements that limit the amount of water diverted from a river/canal, even if there is still water available in the given river/canal. To achieve this varying balance of water sources for each user it is necessary to first define the preferences for the different water sources and then to consider constraints or limits on the maximum amount of water that can be diverted from each source.

The process of calibration consisted then in assigning preferences for different sources of water (obviously this was not necessary for users relying on only one source of water, e.g., Non-Project users F2 and F3) and then imposing maximum flow constraints on those sources. It was assumed for this model that users in the Stone Corral HUC will prioritize surface water over ground water deliveries. After reaching a maximum surface water delivery, defined by canal conveyance capacities and contract entitlements, users will draw upon ground water until their requirements are fulfilled. Assigning constraints on the surface deliveries was then the major task undertaken in the calibration procedure.

The historic data used to perform the calibration process was composed of the following:

- Regional water budget performed by the California DWR on the Planning Area 506 (which is equivalent to the Stone Corral HUC) based on 1998 data.
- Water level for a selection of wells located in the Colusa and Glenn counties
- Historic water surface deliveries to CVP contractors
- Historic crop production in the Colusa and Glen counties

Before applying surface water deliveries constraints, the disaggregated model was run without them (hereafter the "un-calibrated" model). Results from the run were compared to historic data shown Tables A-4 and A-5 and FigureA-1. TableA-4 shows a comparison between a summarized water budget performed by California DWR for their Planning Area 506 (column 1) and a water budget performed using the output results from the un-calibrated model (column 3). The un-calibrated model predicted greater project surface water deliveries than reflected in the regional historic analysis. This improved surface water reliability then resulted in less groundwater pumping. Looking now at a more detailed level, TableA-5 compared historic (period 1994–1998) and modeled water deliveries for all CVP contractors as they are grouped in the Stone Corral HUC. The un-calibrated model shows water deliveries that are in general in good accordance with historic values except the case of South TCCA users which receive much less water from the Tehama Colusa Canal that predicted in the model. Finally, Figure A-1 shows groundwater level trends from several wells in the Colusa Basin and the trends as modeled in WEAP. The blue thick line represents the results from the un-calibrated model that shows in general a water level trend in accordance with data taken from well logs in the basin.

The results from the un-calibrated model justify the inclusion of constraints on surface water deliveries in order to reflect the actual balance of surface and ground water use in the basin. For major CVP contractors, data on annual contracts available from the input files of the CalSim-II model (DWR/USBR, 2002) was used. Comparable sets of data were not available for the non-district CVP and non-CVP contractors in the region who have access to local surface water. This is a shortcoming in the calibration procedure especially for Non-District users along the Sacramento River (users code F1) as they represent a large proportion of the total acreage in Stone Corral HUC (more than 30%). In order to impose a realistic surface water delivery constraint for these users data provided by DWR's 1998 land survey was considered. Included in this land survey data is sources of water for all farmers within each region. According to this land survey data, non-district users had almost 15,000 Has of land irrigated by ground water. This represents around 25% of total irrigated acreage for these users. The estimated of surface water delivery constraint for these users was 3/4 of total requirements of almost 400 TAF/year, or 300 TAF.

As can be seen from these results, the model shows a good agreement in terms of CVP deliveries both at the regional (see water budget results in column 4 in Table A-4) and detailed level (see detailed CVP deliveries in Table A-5). The results for the trend on groundwater levels also show a good agreement with the calibrated model (red thick line in Figure A-1).

Table A-4. Water budget for Colusa Basin (Stone Corral HUC)

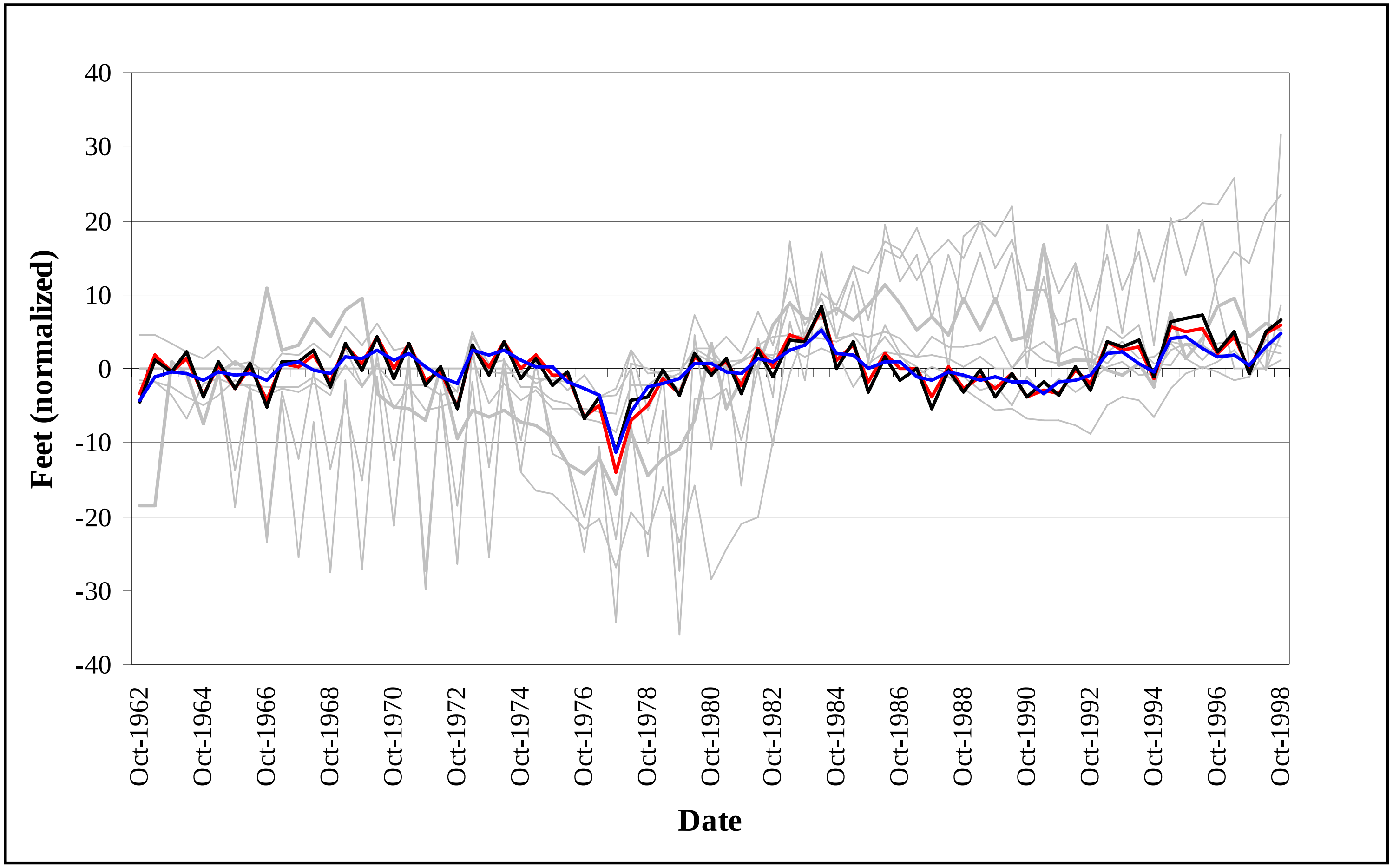
Item	DWR esimtates for PA 506 Colusa Basin	WEAP Model, Stone Corral HUC		
		Aggregated	Disaggregated	
			Un-calibrated	Calibrated
Precipitation	*3,383*	*3,396*	*3,396*	*3,396*
Project Deliveries				
Central Valley Project :: Base Deliveries	889			
Central Valley Project :: Project Deliveries	211	*1,492*	*1,152*	*1,085*
Other Federal Deliveries	1			
TOTAL	*1,101*			
Groundwater Extractions - Unadjudicated	*334*	*240*	*163*	*343*

Table A-5. CVP contractors: WEAP vs. actual deliveries (in TAF)

Summary for CVP users in Stone Corral

		Years										
		1994		***1995***		***1996***		***1997***		***1998***		**Average error**
User		***Deliveries***	***Error***	***Deliveries***	***Error***	***Deliveries***	***Error***	***Deliveries***	***Error***	***Deliveries***	***Error***	
Glen Colusa ID B	Historic	589		573		548		583		528		
	WEAP Un-calibrated	597	*1%*	482	*-16%*	557	*2%*	592	*2%*	459	*-13%*	**-5%**
	WEAP Calibrated	594	*1%*	482	*-16%*	557	*2%*	592	*1%*	459	*-13%*	**-5%**
Tehama Colusa Canal Authority North A1	Historic	58		87		107		105		68		
	WEAP Un-calibrated	141	*142%*	105	*21%*	124	*16%*	137	*30%*	96	*40%*	**50%**
	WEAP Calibrated	134	*131%*	105	*21%*	124	*16%*	134	*27%*	96	*40%*	**47%**
Tehama Colusa Canal Authority South A2	Historic	77		88		100		121		82		
	WEAP Un-calibrated	245	*220%*	185	*111%*	215	*116%*	238	*97%*	170	*108%*	**130%**
	WEAP Calibrated	119	*56%*	110	*25%*	117	*18%*	118	*-3%*	103	*26%*	**24%**
Settlement Stone	Historic	408		385		378		426		308		

Corral close to SAC C1	WEAP Un-calibrated	458	*12%*	359	*-7%*	414	*10%*	453	*6%*	332	*8%*	**6%**
	WEAP Calibrated	451	*11%*	359	*-7%*	414	*10%*	451	*6%*	332	*8%*	**5%**
Settlement Stone Corral far from SAC C2	Historic	67		75		94		98		64		
	WEAP Un-calibrated	123	*84%*	100	*34%*	115	*23%*	122	*25%*	96	*50%*	**43%**
	WEAP Calibrated	122	*84%*	100	*34%*	115	*23%*	122	*24%*	96	*50%*	**43%**



Notes:
Gray thin lines: selected wells in the Colusa Basin
Black thick line: aggregated model after calibration
Blue thick line: disaggregated model no calibration
Red thick line: disaggregated model with calibration

Figure A-1. GW levels Stone Corral Aquifer

Appendix B:
Development of Adaptation Strategies

B.1. Increased Irrigation Efficiency

As mentioned before it was assumed for the development of this project, that there are exogenous (not climate dependant) forces (regulatory pressure) that will increase irrigation efficiency over time on the 21st century regardless of climate conditions. The assumption is that these increments of efficiency improvement occur gradually over the first half of the century until they reach a maximum level by 2050.

These improvements will be different for different crops as can be seen in Table B-1. The data in the table is estimated assuming orchard acreage to be entirely irrigated with low volume irrigation systems (e.g., drip) by 2050. Similarly, we assume 100% of row crop acreage, including vegetables, and 50% of field crop acreage will be served by low volume systems by 2050. Rice acreage, on the other hand, will be irrigated by gravity fed irrigation in 2050, as it is today. The resulting impact on applied water use of these changes in irrigation methods is indicated in Table B-1. For example, applied water to orchards is expected to fall to 84% of current levels. The drop in applied water in this case is relatively small, since most orchard acreage is currently irrigated with low volume methods.

In order to represent these improvements in the Sacramento WEAP model the parameters that determine the irrigation process in the model were modified. Under WEAP representation of hydrology and land use demands, a watershed unit can be divided into N fractional areas representing different land uses/soil types, and a water balance is computed for each fractional area, j of N. The process represented in each fractional area (percolation, surface runoff, interflow, ET) have associated certain calibrated parameters such as the Leaf Area Index, that determines the amount of surface runoff or the root zone conductivity that determines the amount of water that percolates into the groundwater from the soil. All these physical parameters were previously calibrated (see Yates et al. 2005c) to represent current conditions in the Sacramento Valley. Two more parameters are used to represent irrigation practices when soil moisture is not sufficient to meet ET requirements. The first of these parameters called the lower irrigation threshold ($IrrThrLwr_j$) represents the soil moisture level at which irrigation will be required (i.e., any time the soil moisture is below $IrrThrLwr_j$ irrigation is called) to increase the soil moisture up until it reaches an upper irrigation threshold ($IrrThrUpr_j$). Considering that these two parameters were directly related to irrigation procedures they were chosen as parameters to be modified to represent improvements in irrigation efficiency.

Reducing $IrrThrLwr_j$ would lower supply requirements because holding all other parameters constant now irrigation is called less frequently, i.e., the level of soil moisture tolerance before external supplies of water are needed are increased. On the other hand reducing $IrrThrUpr_j$ also implies less water requirements because now every time an irrigation call is made, there will be less need of water to fill the bucket until we reached the soil moisture threshold level. However at the same time less irrigation is required, soil moisture is reduced (the bucket is filled to a lower level) and hence ET, percolation and surface runoff are reduced. The two later effects are expected under an improvement in irrigation efficiency but the former not anticipated. Modifying both parameters (allowing them to increase and decrease) created different water supply requirements holding ET at reasonable levels.

Using a reduced time period (1962-1980) of the original aggregated model of the Sacramento Valley, changes in these parameters were carried out to understand their impact on water supply requirements for each crop. The result from this experimentation was a collection of data points representing different changes in the parameters with their associated change in water supply requirements and change in ET. Based on this analysis the change in parameters that best represented the target improvement in water supply requirement for each crop is shown in Table B-1.

Table B-1. Improvements in irrigation efficiency by 2050, associated parameter change

crop	Percent of original supply requirement by 2050	Initial Lower Threshold	Initial Upper Threshold	Change in Lower Threshold	Change in Upper Threshold
cereals	86%	40%	55%	-15%	0
oilcrops	86%	30%	40%	-10%	0
orchards	84%	40%	45%	-15%	5%
pasture	86%	40%	50%	-5%	-5%
rowcrops	96%	40%	50%	-10%	0

B.2. Shifts in Cropping Patterns

The determination of cropping patterns is made each year prior to planting. WEAP supplies water for irrigation to several land use classes. Each land use class has its own irrigation demand pattern, which depends upon the time of planting, the crop coefficient, and reference evapotranspiration. In general, crops require water for irrigation between the months of February and October. As such, February 1st was chosen as the date for adjusting the cropping patterns for CVP contractors based upon an evaluation of water supply conditions in the Sacramento Valley.

B.3. Derivation of the Crop Adaptation Equations

The HUC's grow a mix of cereal, orchard, pasture, rice and row crop acreage. The share of crop acreage in each HUC varies as a function of changes in the supply of surface water and depth to groundwater. The function is derived from a multinomial regression analysis of synthetic data of crop shares generated by the Central Valley Production

Model for regions 3, 3b, 4, and 5. These regions cover a portion of the northwestern Central Valley, very roughly coincident with Glenn and Colusa Counties.

The data were generated from CVPM model runs assuming the base water supply and groundwater depth, a 10% decrease from base water supply, a 20% decrease from base water supply, a 100 foot drop in the groundwater depth and a 200 foot drop in the groundwater depth. These model runs provided 408 synthetic estimates of crop shares across a range of different regional, water supply and groundwater depth assumptions. The multinomial logit analysis of this data was used to derive the following equation coefficients (Table B-2).

Table B-2. Multinomial logistic regression results

Coefficient output and z statistics

Crop	Cereal		Orchard		Pasture		Rice		Row	
	coefficient	z statistic	coefficient	z statistic	coefficient	z statistic	coefficient	z statistic	coefficient	z statistic
depth	**-0.004**	-22.4	**-0.004**	-21.4	**-0.005**	-20.8	**-0.004**	-24.7	**-0.004**	-20.7
percent supply	**6.224**	31.7	**5.992**	30.6	**6.799**	29.0	**6.568**	35.8	**5.999**	29.6
region 3	**-1.287**	-27.2	**-2.473**	-50.8	**-1.569**	-31.2	**0.609**	12.1	**-0.414**	-8.4
region 4	**-0.130**	-2.6	**-1.412**	-28.3	**-2.201**	-37.9	**0.681**	12.8	0.111	2.2
region 5	**-1.361**	-28.2	**-0.405**	-8.8	**-1.518**	-29.7	**0.931**	18.3	**-2.074**	-38.1
constant	**-2.683**	-14.4	**-2.235**	-12.0	**-3.481**	-15.6	**-3.817**	-21.8	**-3.074**	-15.9

Combined Regression Coefficients

	Cereal	**Orchard**	**Pasture**	**Row**	**Rice**
	B1	B2	B3	B4	B5
depth	-0.0044	-0.0042	-0.0048	-0.0045	-0.0042
persup	6.2245	5.9918	6.799	6.5681	5.9985
reg3	-1.2872	-2.4727	-1.5688	0.609	-0.4143
reg4	-0.1303	-1.4122	-2.2013	0.6809	0.1112
reg5	-1.361	-0.4054	-1.518	0.931	-2.0739
cons	-2.6829	-2.2346	-3.4806	-3.8168	-3.0742

Number of obs = 173597
Log likelihood = -259222.93
Pseudo R2 = 0.0790
(Outcome: Fallow is the comparison group)

The logit regression coefficients have the correct sign and are highly significant, with the exception of two regional dummy variables, as judged by the z statistics in Table B-3. The logit regression coefficients are manipulated to derive crop share equations (Table B-3).

In Table B-3, P_0-P_5 refer to the estimated crop shares, B refers to the estimated vector of logit coefficients associated with each crop type, and X refers to the matrix of independent variables including the water supply and groundwater depth.

Table B-3. Crop share equations

Fallow	P_0	$\Pr(y=0)=\dfrac{1}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$
Cereal	P_1	$\Pr(y=1)=\dfrac{e^{XB_1}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$
Orchard	P_2	$\Pr(y=2)=\dfrac{e^{XB_2}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$
Pasture	P_3	$\Pr(y=3)=\dfrac{e^{XB_3}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$
Rice	P_4	$\Pr(y=4)=\dfrac{e^{XB_4}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$
Row	P_5	$\Pr(y=5)=\dfrac{e^{XB_5}}{1+e^{XB_1}+e^{XB_2}+e^{XB_3}+e^{XB_4}+e^{XB_5}}$

The accuracy of the crop share equations in predicting changes in crop acreages was evaluated against changes in historical crop shares during the 1990-1992 period, the worst drought on record in the Sacramento Valley. The logit equations were calibrated to fit base 1989 Glenn and Colusa County crop shares, just prior to this drought. The calibration procedure involves changing the constant term in Table B-3 so that predicted crop shares matches base period crop shares. 7

** The constant term associated with each crop share (Pi) in the County in the base period is derived as follows (continued at the bottom of the next page):

$$\frac{1}{\sum_i e^{XB_i}+1}=P_0$$

$$\sum_i e^{XB_i}+1=\frac{1}{P_0}$$

$$\frac{e^{XB_i}}{\sum_i e^{XB_i}+1}=P_i$$

$$\frac{e^{XB_i}}{\sum_i e^{XB_i}+1}=P_i$$

Relative surface deliveries to Glenn and Colusa Counties during the 1987-1994 period are assumed to match CVP north of Delta deliveries. This index suggests that surface deliveries to these Counties fell 30% between 1989 and 1992, and rose at the end of the drought after 1993 (Table B-4. Average groundwater depth in this region declined slightly according to DWR groundwater depth records (Table B-4).

Table B-4. Water supply and depth to groundwater trends in Glenn and Colusa Counties

	Water Supply			Depth to Groundwater	
	CVP Deliveries, NOD	Total CVP, NOD	Total CVP NOD Index	Colusa and Glenn County	Reference to 85 feet in 1989
1987	1557692	1,900,569	1.03	36.68	
1988	1483088	1,834,060	0.99	39.14	85
1989	1500561	1,851,533	1.00	41.47	85
1990	1458159	1,770,766	0.96	43.23	87
1991	1189512	1,385,392	0.75	43.95	89
1992	1155254	1,276,833	0.69	38.98	87
1993	1241494	1,521,284	0.82	44.04	89
1994	1283860	1,486,920	0.80	37.03	85

Source:
Water Supply: CVP Deliveries in the Sacramento Valley. U. S. Bureau of Reclamation
Central Valley Operations Web site: http://www.usbr.gov/mp/cvo/deliv.html
Depth to groundwater averaged across Glenn and Colusa County. Department of Water Resources groundwater well depth records.

A comparison of historic and predicted Glenn and Colusa County crop shares suggests that the crop share equations provide only a rough approximation of drought period crop trends (Tables B-5 and B-6; FiguresB-1 and B-2). The drought precipitated relatively large declines in rice (4%) and cereal (-1.5%) shares accompanied by a large rise in fallowing (5%). Historic shares of other crops showed less pronounced trends. Interestingly, pasture tended to rise over the period rather than fall as predicted.

The crop share equations predicted the decline in rice and the rise in fallowing shares with some accuracy, somewhat under predicting both crop trends. The equations failed to predict the slight historic rise in pasture acreage; predicting a drop in pasture share instead. In addition, the crop share equations predicted land fallowing would peak in 1992 but the historical data indicate that land fallowing actually peaked in 1991 instead. The discrepancy between predicted and historical crop acreage trends may reflect an error in the historical water supply data used in our predictions.

$$e^{XB_i} = \frac{P_i}{P_0}$$

$$XB_i = \ln(P_i) - \ln(P_0)$$

$$B_0 = \ln(P_i) - \ln(P_0) - XB_i$$

Table B-5. Crop adaptation model: predicted and historic crop shares in Colusa County

Historic Crop Shares

Year	Cereals	Orchard	Pasture	Rice	Vegetables	Fallow
1989	24.0%	21.5%	17.5%	33.9%	3.1%	0.0%
1990	26.3%	21.7%	16.9%	30.7%	3.0%	0.9%
1991	22.8%	22.6%	18.7%	26.1%	2.3%	5.5%
1992	22.4%	24.1%	17.9%	31.2%	1.6%	2.0%
1993	25.5%	25.2%	20.0%	37.8%	2.0%	-7.6%

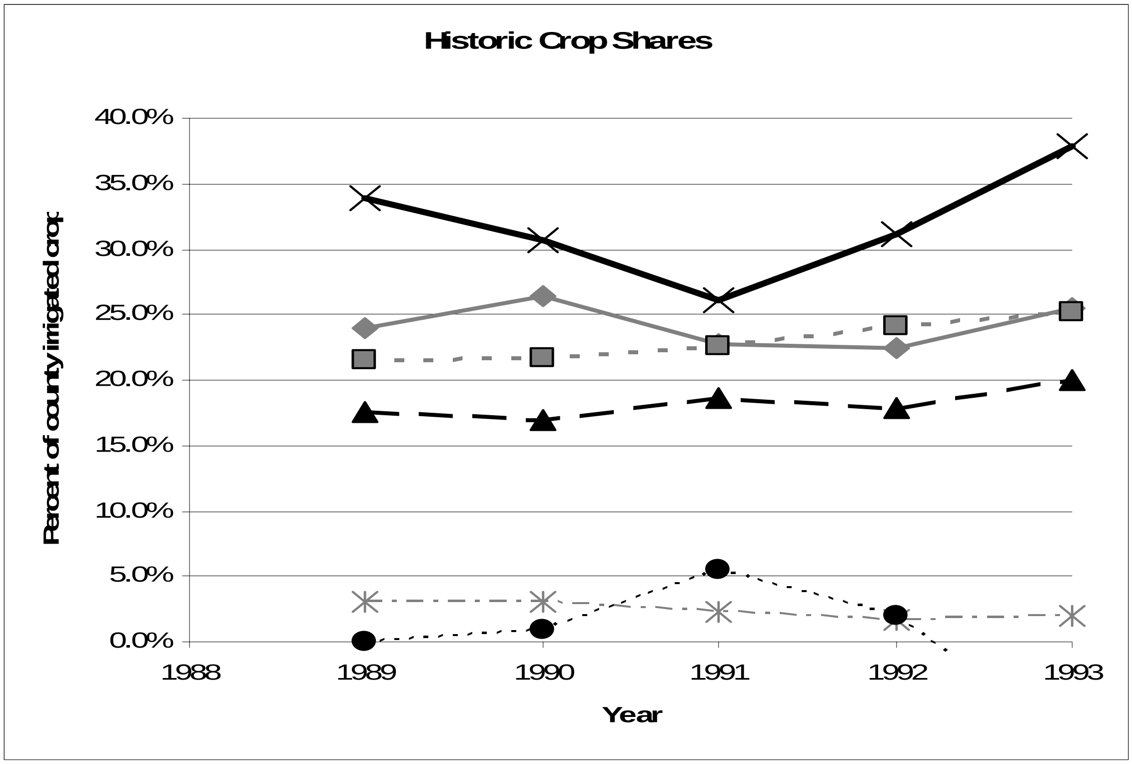
Predicted Crop Shares

Year	Cereals	Orchard	Pasture	Rice	Vegetables	Fallow
1989	23.7%	21.2%	17.4%	33.6%	3.1%	1.0%
1990	23.8%	21.6%	17.0%	33.2%	3.1%	1.3%
1991	23.7%	22.5%	15.0%	30.8%	3.2%	4.7%
1992	23%	23%	14%	30%	3%	7%
1993	24%	22%	16%	32%	3%	3%

Estimation Error, Predicted Minus Historic Crop Shares

Year	Cereals	Orchard	Pasture	Rice	Vegetables	Fallow
1989	-0.2%	-0.2%	-0.2%	-0.3%	0.0%	1.0%
1990	-2.5%	-0.1%	0.0%	2.5%	0.1%	0.4%
1991	0.9%	-0.1%	-3.7%	4.7%	0.9%	-0.8%
1992	0.9%	-1.5%	-3.7%	-1.5%	1.6%	4.9%
1993	-1.6%	-2.9%	-4.2%	-6.0%	1.2%	10.7%

Source:
Historic crop shares from County Agricultural Commissioner Reports for Glenn and Colusa County.
Predicted shares from logit model crop share equations, calibrated to fit Glenn and Colusa Coutny 1989 crop shares



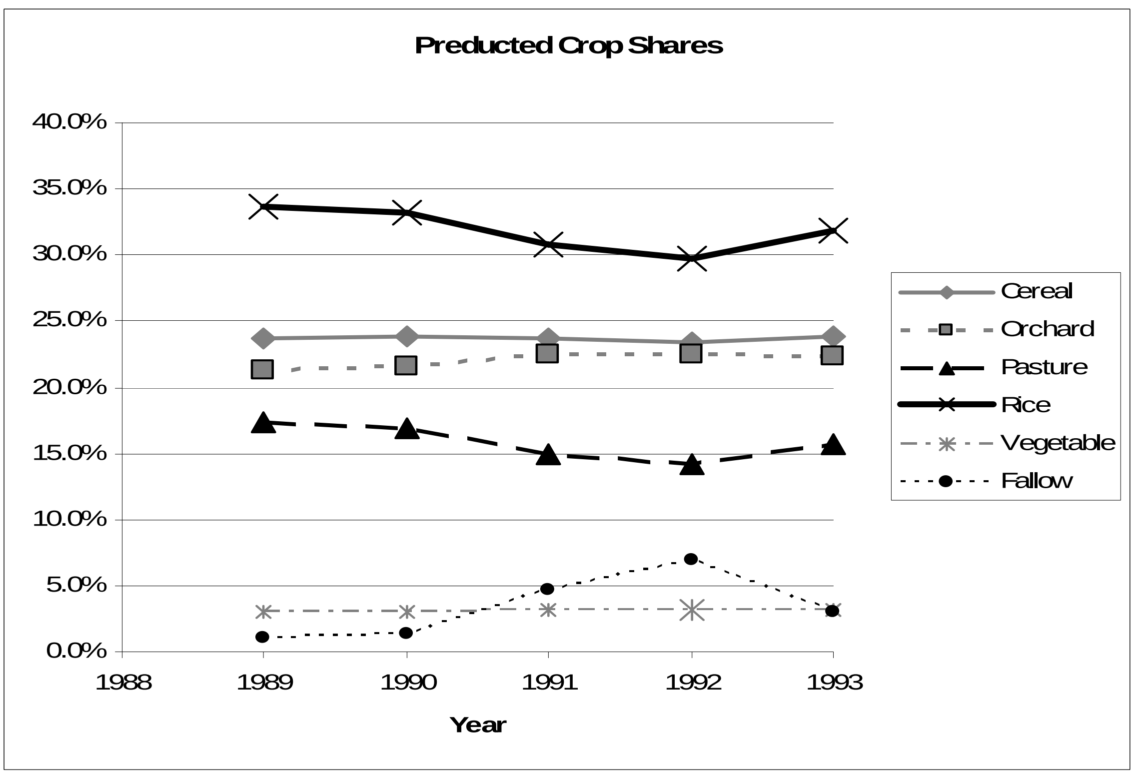


Figure B-1. Historic and predicted crop shares in Colusa County

Table B-6. Crop adaptation model: predicted and historic crop shares in Glenn County

Historic Crop Shares						
Year	**Cereals**	**Orchard**	**Pasture**	**Rice**	**Vegitables**	**Fallow**
1989	27.2%	15.7%	17.6%	35.0%	4.5%	0.0%
1990	28.6%	15.7%	17.0%	31.9%	4.3%	2.1%
1991	25.0%	16.2%	18.7%	27.2%	3.6%	7.7%
1992	24.5%	17.2%	18.0%	32.3%	2.7%	4.4%
1993	30.8%	18.1%	20.1%	39.4%	3.2%	-9.7%
Predicted Crop Shares						
	Cereals	**Orchard**	**Pasture**	**Rice**	**Vegitables**	**Fallow**
1989	27.0%	15.5%	17.4%	34.7%	4.4%	1.0%
1990	27.1%	15.8%	17.0%	34.3%	4.5%	1.3%
1991	27.0%	16.5%	15.1%	31.9%	4.7%	4.8%
1992	27%	16.5%	14.4%	30.8%	4.7%	7.0%
1993	27%	16.3%	15.8%	32.9%	4.6%	3.1%
Estimation Error, Predicted Minus Historic Crop Shares						
	Cereals	**Orchard**	**Pasture**	**Rice**	**Vegitables**	**Fallow**
1989	-0.3%	-0.2%	-0.2%	-0.4%	0.0%	1.0%
1990	-1.5%	0.1%	0.1%	2.4%	0.2%	-0.8%
1991	2.1%	0.3%	-3.6%	4.7%	1.1%	-3.0%
1992	2.1%	-0.7%	-3.6%	-1.5%	2.0%	2.6%
1993	-3.6%	-1.8%	-4.2%	-6.5%	1.4%	12.8%

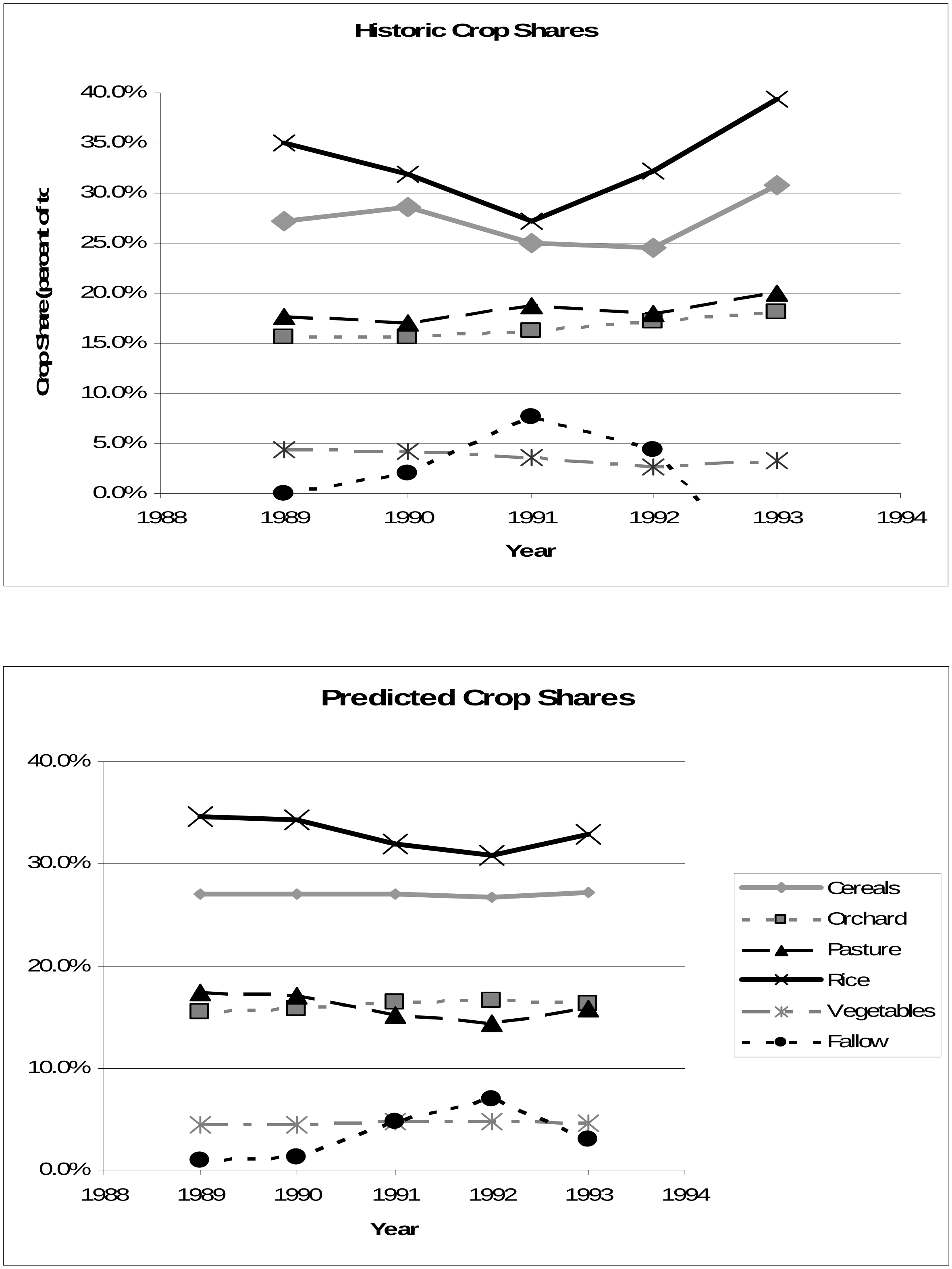


Figure B-2. Historic and predicted crop shares in Glenn County

Crop share equations were developed to show changes in crop acreage and water use in the WEAP model over time. The share equations were developed from a multinomial logit analysis of simulated CVPM model crop share output. The equations were used to "backcast" historical crop trends in Colusa and Glenn Counties. The share equations predicted historical rice and fallow acreage trends during the drought with some accuracy, but delayed by one year. The "backcast" analysis suggests the equations provide a rough indication of crop shifts likely to accompany changes in water supply and groundwater depth in the Sacramento Valley.

B.3.1. Estimating water supply for Sacramento Valley CVP contractors

Each spring the U.S. Bureau of Reclamation (USBR) and California Department of Water Resources (DWR) determine yearly allocations to CVP and SWP contractors based upon current storage in and forecasted inflows to their reservoirs (Shasta, Folsom, Clair Engel, and Oroville). CVP and SWP agricultural contractors are subject to reduced allocations each year, depending upon the anticipated amount of demand that their respective reservoirs can satisfy. CVP Settlement contractors, on the other hand, have their contracted water reduced only in years when the total annual inflow to Shasta is below 3.46 million acre-feet (MAF). In these dry (or Shasta critical) years, settlement contractors are guaranteed only 75 percent of their water contracts.

In order to adjust contract allocations within WEAP based upon water supplies, we must assess current reservoir storage conditions and estimate the expected inflows to reservoirs over the remainder of the water year. Reservoir storage levels can be easily read from previous time step results. Forecasted reservoir inflows, on the other hand, need to be calculated using other hydrologic indicators that the model has access to. For the purposes of this work, reservoir inflows for the period February through September are expressed as a function of the cumulative inflows for the period October through January.

Water supply conditions were estimated using reservoir storage and naturalized streamflow data obtained from the California Data Exchange Center (CDEC). Water supply for CVP settlement contractors was defined as the sum of end of January storage in and forecasted February through September inflows to Lake Shasta. Water supply for CVP agricultural contractors was defined as the sum of end of January storage in and forecasted February through September inflows to Lake Shasta, Folsom, and Clair Engel reservoirs. Finally, water supply for SWP contractors was defined as the sum of end of January storage in and forecasted February through September inflows to Lake Oroville.

Figures B-3 through B-5 show cumulative reservoir inflows for the periods Oct-Jan and Feb-Sep for each of the groups of reservoirs used in calculating CVP and SWP water supplies. The regression equations shown were used in WEAP to estimate forecasted inflows. These forecasts were added to current project water storages to estimate the overall water supply for each project. Note that in each figure the water year 1997 was not included, because a large flooding event in January and a dry spring caused the data to be skewed.

Estimations of water supply were used as inputs to the logit regression equations developed to express changes in cropping patterns. For CVP and SWP agricultural contractors, water supplies were expressed relative to an average value (10,800 TAF for the CVP and 5,000 TAF for the SWP). For CVP settlement contractors, water supplies were reduced to 75 percent of full in years when inflows to Shasta were predicted to be below the Shasta critical criteria.

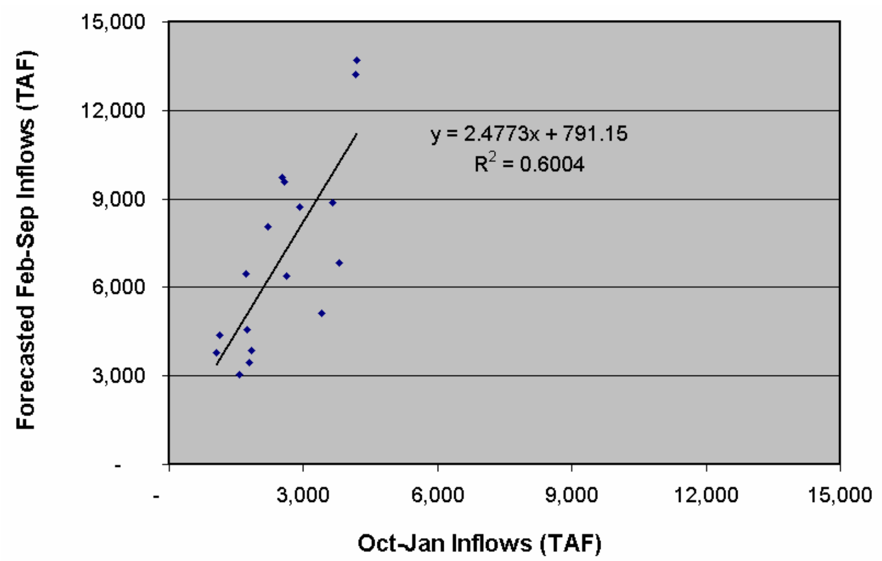


Figure B-3. Total inflow to Shasta, Folsom, and Clair Engel Reservoirs

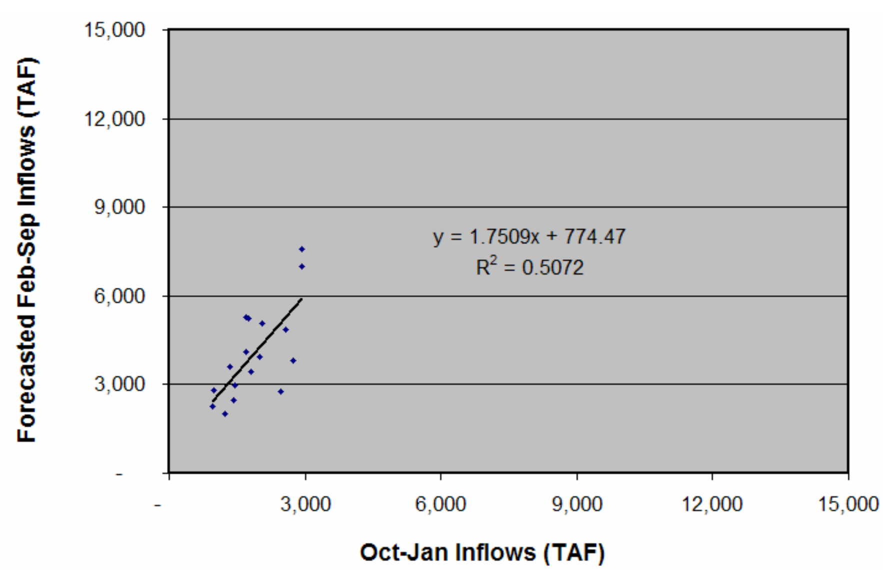


Figure B-4. Total inflow to Lake Shasta Reservoir

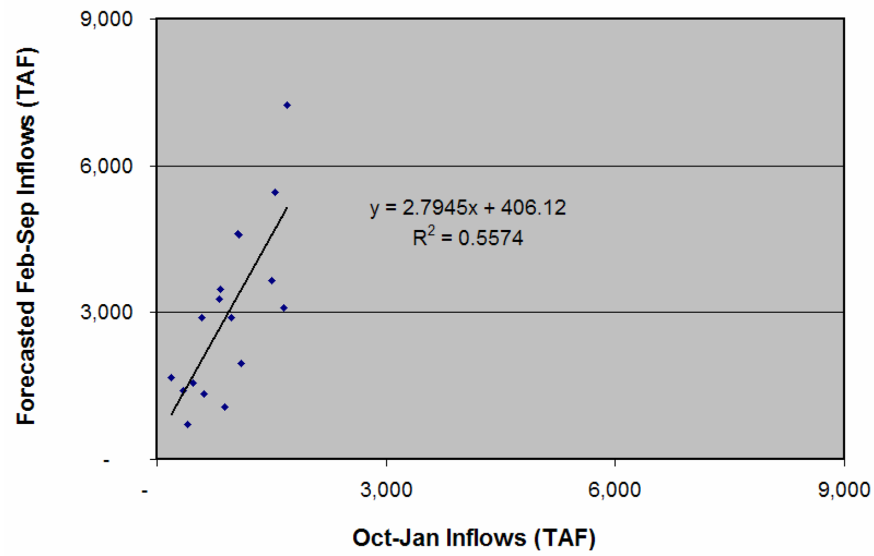


Figure B-5. Total inflow to Lake Oroville Reservoir

B.3.2. Economic Impacts on Agriculture

The economic impacts of different climate scenarios are estimated in WEAP from predicted changes to cropping patterns, crop revenues and crop production costs. The model predicts changes in cropping patterns and irrigation deliveries as described above. Changes in unit crop revenue and costs are estimated assuming current crop yield, revenue and production cost levels projected into the future.

The crop yield, revenue and production cost estimates in the model are taken from crop budgets, assembled by U.C. Cooperative Extension, and U.S.D.A. County Agricultural Commissioner yield and price data. Water costs are taken from unit pumping cost and surface delivery cost figures cited in the U.C. Extension crop budgets and other sources.

Table B-7. Average net revenues for all users (2070-2099 for climate change conditions and 1962-1998 for historic conditions). (Figures in 10^6 \$/year)

	Historic	Climate change scenarios with adaptation			
		PCMB1	PCMA2	GFDLB1	GFDLA2
Farming net revenues (not including water costs)	566	495	498	498	495
Surface water deliveries costs	10	8	8	8	8
Pumping costs	13	11	11	13	36
Net revenues including water costs	**544**	**476**	**478**	**476**	**451**
percent reduction		12%	12%	12%	17%

This analysis provides a rough estimate of the decline in net revenue or farm profit resulting from climate change and decreased water supplies (Table B-4). All climate change scenarios show a reduction in net revenues, due primarily to increased land fallowing and shifts to water conserving crops. The decline is correlated with the predicted drop in water deliveries. For example, the model predicts that the PCM B1, PCM A2, and GFDL B1 scenarios, with moderate impacts on water deliveries, lower net revenue 12 percent. The model predicts that the GFDL A2 scenario, with a larger impact on water deliveries, lowers net revenue 17 percent.